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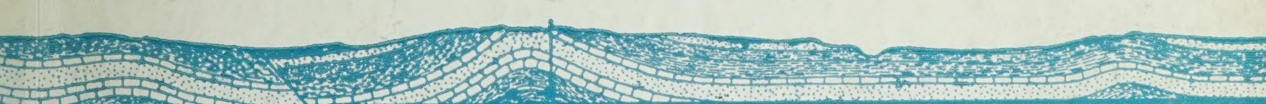
January 1965

GROUND-WATER RESOURCES ALONG CEDAR CREEK ANTICLINE IN EASTERN MONTANA

by

O. JAMES TAYLOR



MONTANA BUREAU
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Butte, Montana

STATE OF MONTANA
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SYMBOLS USED IN THIS REPORT

The following symbols are listed in alphabetical order. Each symbol indicates the basic term usually represented; no attempt is made to show the many and unavoidable duplicate uses. In the text, various subscripts are used in conjunction with these symbols to denote specific applications of the basic terms. A few of the more important combinations of this type are given; others are defined where they appear in the text.

h	Head of water with respect to some reference datum.
h'	Recovered head of water with respect to some reference datum.
k	A constant.
m	Saturated thickness of an aquifer.
p	Pressure in force per unit area.
Q	Rate of discharge or recharge.
r	Radial distance from discharge or recharge well to point of observation.
r_w	Effective radius of a well.
S	Coefficient of storage of an aquifer.
s	Change in head of water, usually expressed as drawdown.
s_w	Change in head of water at a discharging well.
s'	Residual change in head of water usually expressed as residual drawdown.
T	Coefficient of transmissibility of an aquifer.
t	Elapsed time with respect to an initial reference.
t'	Elapsed time with respect to a second reference.
$W(u)$	Well function of u, constant discharge situation.
α	Vertical compressibility of the aquifer skeleton.
β	Compressibility of water; approximate value for average ground-water temperature is 3.3×10^{-6} in^2/lb.
γ	Specific weight of a substance.
γ_0	Specific weight of water at a stated reference temperature; numerically equal to 62.4 lb/ft^3 or 3.61×10^{-2} lb/in.^{3} at 4°C or 39°F.
θ	Porosity of an aquifer.

Ground-Water Resources Along Cedar Creek Anticline In Eastern Montana

by

O. James Taylor

SUMMARY

This report discusses the results of an investigation of the hydrologic system along the Cedar Creek anticline in eastern Montana. In this area the domestic, industrial, and municipal consumers are dependent upon ground water from the relatively thick and continuous aquifer in the Fox Hills Sandstone and basal part of the Hell Creek Formation and from discontinuous and thinner aquifers in the upper part of the Hell Creek Formation and in the Fort Union Formation. The permeable beds that constitute the aquifers were deposited with other, less permeable beds in marine and coastal environments during Cretaceous and Tertiary time. Subsequent folding, uplift, and erosion formed the present configuration of the anticline with the aquifers on both flanks of the structure but absent along the crest. The structure is illustrated both by geologic and by structural contour maps.

The aquifer in the Fox Hills and basal part of the Hell Creek is principally an artesian aquifer, which receives its natural recharge in exposures south of the area of investigation. A small amount of recharge occurs in the outcrop along the western flank of the anticline. A piezometric map of the aquifer shows that the ground-water movement is toward the north. Natural discharge is from springs and seeps into the Yellowstone River.

The discontinuous aquifers of the Fort Union Formation presumably receive natural recharge at various places in the large exposure area of the formation, and the ground water probaby moves toward the north.

Chemical analyses indicate that most of the water in the aquifers on the western flank is very soft but contains abundant sodium, bicarbonate, and sulfate. The water is satisfactory for domestic and livestock uses but unsatisfactory for irrigation.

Industrial water requirements call for the consumptive use of about 4 billion gallons of ground water (an average rate of 360 gallons per minute) in the next 21 years from the aquifer in the Fox Hills and basal part of the Hell Creek on the western flank of the anticline. Predictions were made of the response of the hydrologic system to the combination of artificial withdrawals and natural influences.

Thirty aquifer tests were made, and average values of the coefficients of transmissibility and storage were computed. Good agreement was found between the measured drawdowns due to preliminary industrial pumping and the theoretical drawdowns computed using the Theis equations. Thus, the computed values of the coefficients of transmissibility and storage are believed to be realistic.

The response of the hydrologic system to future withdrawals was calculated on the basis of a proposed pumping schedule and known aquifer characteristics. The image-well theory was used to account for the hydrologic boundaries that affect drawdown in the aquifer. The predicted drawdown in the aquifer after 5, 10, and 21 years of pumping is shown on maps by means of contours. The pressure in some domestic and stock wells will be affected by the drawdown during the first 10 years of pumping. Municipal wells in the area will be affected only slightly. Owing to the reduction in the pumping rate with time, most of the artesian pressure will be recovered by the end of the proposed 21-year pumping period.

It is recommended that increased emphasis be placed on conservation of the important ground-water resources in eastern Montana and that the assumptions and predictions made for this analysis be checked periodically.

INTRODUCTION

This report discusses the results of a cooperative investigation made by the Ground-Water Branch of the U. S. Geological Survey and the Montana Bureau of Mines and Geology. The investigation and report were under the direct supervision of Mr. Charles Lane, district geologist, U. S. Geological Survey.

LOCATION AND EXTENT OF AREA

The area of investigation is along the Cedar Creek anticline in east-central Montana and extends from T. 5 N. to T. 14 N. and from R. 53 E. to R. 61 E., an area of about 2,600 square miles (Fig. 1). The investigation was concentrated on the western flank of the anticline, where greater ground-water development is anticipated. The area is drained by Little Beaver Creek, O'Fallon Creek, Cabin Creek, and Beaver Creek. The principal towns are Baker, Plevna, Mildred, Ismay, Willard, Ollie, Carlyle, and Marsh.

PREVIOUS INVESTIGATIONS

Perry (1931) made ground-water studies in eastern and central Montana and in southeastern Montana (1935). Geologic and structural contour maps of the Cedar Creek anticline were prepared by Erdmann and Larsen (1934) and Dobbin and Larsen (1934). Brown (1949) mapped Paleocene deposits in the area and studied fossil plants in the Fox Hills Sandstone (1937). Dobbin and Reeside (1939) investigated the contact of the Fox Hills Sandstone and Lance Formation, as did Jeletsky (1962) in discussing the Mesozoic-Cenozoic boundary.

PURPOSE AND SCOPE OF PRESENT INVESTIGATION

This investigation was made in order to determine and describe the hydrologic system and how it operates, the chemical quality and suitability of the ground water for domestic and agricultural use, and the probable effects of present and proposed withdrawals from the system. The field work was begun in the fall of 1962 and completed in the spring of 1964, but observations in the study area will be continued through June 1965.

ACKNOWLEDGMENTS

Many persons contributed to the investigation and report by supplying information that otherwise would have been unobtainable. The cooperation of the Shell Oil Company in supplying geologic, hydrologic, and engineering data is gratefully acknowledged. Special thanks are due to Shell personnel—including H. L. Garrett, geologist, David Frawley, engineer, Harold Thompson, former division production manager, and Al Ireson, division exploitation engineer, for their help and suggestions during the investigation.

Engineering data by Ross K. Petersen, consulting ground-water hydrologist for the Shell Oil Company and the City of Baker, were made available for use in this report and are so acknowledged where presented.

Dr. S. L. Groff, head, Ground-Water and Fuels Division of the Montana Bureau of Mines and Geology, assisted the author in a reconnaissance of the study area.

The assistance and advice of S. W. Lohman, research geologist, and R. W. Stallman, research engineer, of the U. S. Geological Survey, Denver, Colorado, is hereby acknowledged.

Residents of the area were most cooperative in providing information on wells, allowing access to their property, and permitting pressure measurements and aquifer tests to be made on their wells.

DESCRIPTION OF HYDROLOGIC SYSTEM

Large quantities of water are stored in oceans, in continental surface and subsurface reservoirs, and in the atmosphere. Such storage is temporary insofar as there is a constant interchange of water from one environment to another. The endless interchange of water is known as the hydrologic cycle. Ground water represents one important phase of the hydrologic cycle.

In a local area the occurrence, storage, and movement of water is known as the hydrologic system. An investigation of the ground and surface water of the hydrologic system also involves a study of the climate, because precipitation is the principal source of all ground and surface water. The geology must also be considered, because the geologic formations form the framework for the storage and movement of ground and surface water.

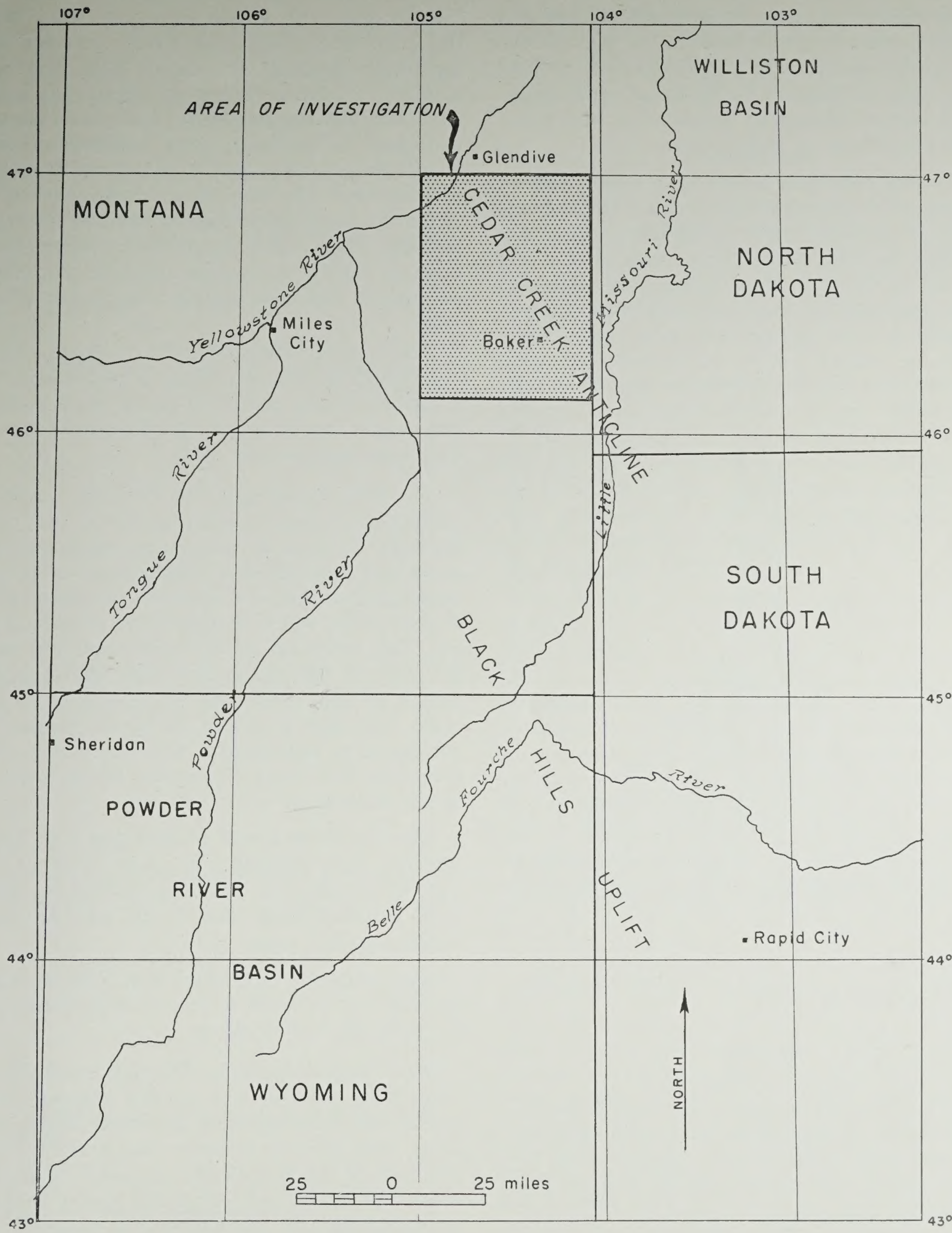

Figure 1.—Index map showing area of investigation.

CLIMATE

The climate of east-central Montana is continental in character and is marked by the following features: abundant sunshine, low relative humidity, light rainfall, moderate wind movement, a large diurnal change in temperature, and pronounced extremes of temperature.

A 25-year record for Baker, Montana, indicates the mean annual precipitation is about 13.3 inches, most of which falls in late spring and early summer (Fig. 2). Other weather stations in the vicinity of the Cedar Creek anticline have recorded similar amounts and yearly distributions of precipitation.

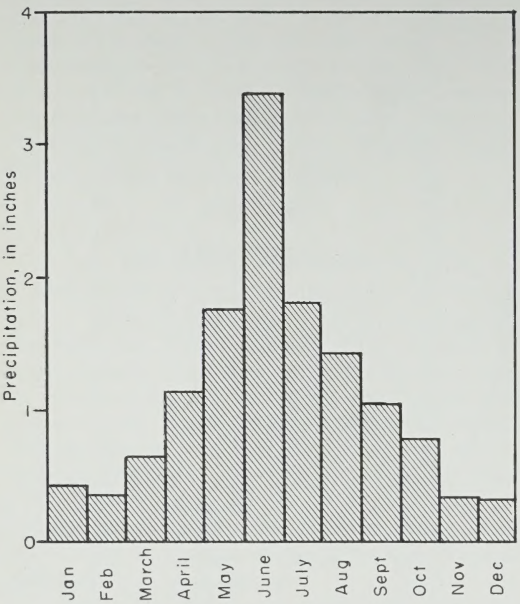

Figure 2.—Mean monthly precipitation at Baker, Montana, for 1931-55.

GEOLOGY

GEOLOGIC FORMATIONS

The stratigraphic nomenclature used in the region has been changed since much of the original work was done. Figure 3 shows the currently accepted names and boundaries of stratigraphic units used in this report.

Upper Cretaceous Series

Pierre Shale. — The oldest formation exposed in the study area is the Pierre Shale, which consists of marine shale and sandstone of Late Cretaceous age. The Pierre is exposed only along the crest of the anticline where younger beds have been removed by erosion. (See Plate 1 in pocket.) Outcrops consist of impure dark-gray shale that contains bentonite, concretions as much as 1 foot in diameter, large boulders of sandstone, gypsum veins and crystals, and local beds of sandstone. The shale in the upper part of the formation is relatively impervious and not water bearing. Deep sandstones in the Pierre are water bearing, but the water generally is of poor chemical quality and may contain natural gas (Perry, 1935).

The contact between the Pierre Shale and the overlying Fox Hills Sandstone is transitional. The transitional beds consist of sandy shale containing concretions, phosphatic pebbles, and aragonite (Erdmann and Larsen, 1934).

Fox Hills Sandstone.—The Fox Hills Sandstone (Upper Cretaceous) consists of marine and brackish-water deposits of cross-bedded sandstone, siltstone, and shale (Dobbin and Reeside, 1929). The upper part consists of a light-gray sandstone about 40 feet thick, which is named the Colgate Member. The sandstone in the lower unnamed member is fine to medium grained, light brown, yellow brown, or light green, and contains some concretions. The sand grains in the lower member are variegated as contrasted to the sand grains of the overlying Hell Creek Formation, which are more nearly uniform in color.

The Fox Hills ranges in thickness from 100 to 150 feet. It is exposed in a narrow belt on each side of the anticline, as shown on Plate 1. Exposures of the Colgate Member are poor or absent in the southern part.

The sandstone beds of the Fox Hills are water bearing and yield soft water, which is satisfactory for domestic and stock use.

Hell Creek Formation.—The Hell Creek Formation is Late Cretaceous in age and consists of nonmarine and brackish-water sandstone, shale, mudstone, and siltstone (Dobbin and Reeside, 1929). The base of the Hell Creek commonly consists of about 100 feet of light-brown to green, medium- to coarse-grained, cross-bedded sandstone. The sandstone characteristically contains abundant 1-inch sandstone concretions with black sooty cores that are surrounded by orange or yellow layers.

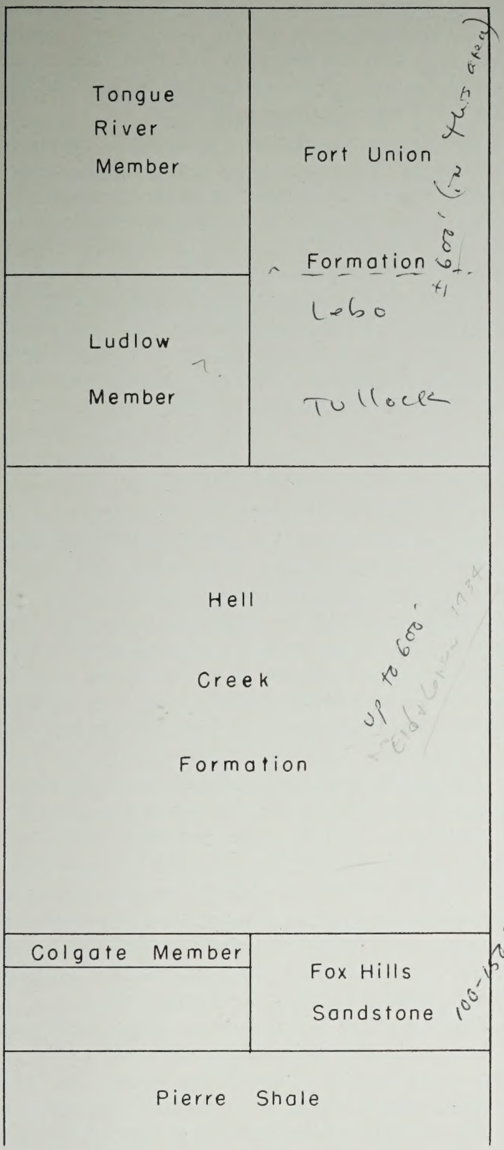

Figure 3.—Stratigraphic nomenclature used in eastern Montana.

The upper part of the Hell Creek consists of sandstone, siltstone, and mudstone. The Hell Creek crops out on both flanks of the anticline and attains a maximum thickness of about 600 feet (Erdmann and Larsen, 1934).

The basal sandstone of the Hell Creek is in contact with the Fox Hills Sandstone, and these sandstones constitute a relatively thick and continuous aquifer. This aquifer yields water for many towns and ranches in eastern Montana.

Paleocene Series

Fort Union Formation. — Overlying the Hell Creek Formation is the Fort Union Formation of Paleocene age. Perry (1935) regarded the Fort Union Formation and Hell Creek Formation as coastal plain deposits.

The Fort Union has been divided into three members in eastern Montana by some workers: a lower member known as the Tullock, a middle member known as the Lebo Shale, and an upper member known as the Tongue River. Difficulties in distinguishing the contact between the Tullock and the Lebo caused Perry (1935) and Jeletsky (1962) to use the name Ludlow in this area. Their classification is followed in this report, and the Fort Union Formation is divided into the Ludlow and Tongue River Members.

The Fort Union attains a maximum thickness of 600 feet in the study area but ~~thickens to the west~~. Both members are composed of interlayered beds of shale, sandstone, siltstone, lignite, and limestone, which are difficult to trace laterally because of facies changes. The Tongue River Member contains clinker beds, which are very resistant to erosion. Differential erosion has produced typical badlands, and the variety of color in the beds adds to the striking appearance of the resulting landscape of the Fort Union. The Fort Union is exposed over very wide areas in eastern Montana and in Wyoming, North Dakota, South Dakota, and Canada.

Many shallow water wells in eastern Montana produce water from the sandstone and coal beds in the Fort Union. North of Ollie and Carlyle, a good well may be obtained at a shallow depth in the Fort Union, hence few wells have been drilled to the aquifer in the Fox Hills and basal part of the Hell Creek. Perry (1931) noted that most of the water wells are less than 200 feet deep. Two or three test holes may have to be drilled to obtain a satisfactory well, and the yield of the well may decline within a few years. The ground water in the Fort Union generally is harder than water from the aquifer in the Fox Hills and basal part of the Hell Creek.

STRUCTURAL GEOLOGY

The structure of the region is shown on Plate 1 by means of structural contours that represent the altitude of the base of the Fox Hills Sandstone. Control points for the contours were obtained from logs of oil and gas wells. Thus, the structural contours provide a convenient method of expressing the structure of the Fox Hills Sandstone over a wide area. The contours are generalized and may be in error as much as 75 feet at some points.

The structure of the Cedar Creek anticline, as intepreted from the structural contour map and surface exposures, can be described as follows: Cedar Creek anticline is an asymmetric fold whose axial line trends about N. 30° W. The beds on the western flank dip as much as 850 feet per mile near the crest of the anticline. Beds on the eastern flank dip more gently at about 70 feet per mile into the Williston Basin. Several normal faults have been mapped on the eastern flank. The anticline plunges to the northwest, and north of the study area the Pierre Shale, Fox Hills Sandstone, and Hell Creek Formation crop out for only a few miles.

Two related structures, the Sheep Mountain syncline and the Ekalaka syncline (Plate 1), are west of the Cedar Creek anticline. The structures are nearly parallel to the axis of the anticline and also plunge to the northwest. West of these structures the beds dip gently to the north.

On the tectonic map of the United States (U. S. Geol. Survey and Am. Assoc. Petroleum Geologists, 1962) the Cedar Creek anticline seems to merge with the Black Hills uplift to the south, and the two structures may be related. The Black Hills uplift, the Cedar Creek anticline, the Poplar dome, and the Regina - Hummingbird trough are all along the Nemo-Estes structural trend (DeMille, Shouldice, and Nelson, 1964).

GEOLOGIC HISTORY

The geologic history of the area has been discussed recently by Jeletsky (1962) and H. L. Garrett (written communication, 1963). At the time of deposition of the Pierre Shale, Fox Hills Sandstone, and Hell Creek Formation, the Late Cretaceous seas were regressive toward the east and south. Formational contacts do not coincide with time lines, and the formations increase in age toward the west.

The uplift and folding that formed the Cedar Creek anticline occurred throughout much of middle Tertiary time according to H. L. Garrett (oral communication, 1964). The Eocene, Oligocene, and Miocene Series in the region are represented by isolated remnants left by the erosion that followed deposition and uplift.

The Yellowstone River is believed to date from the end of Cretaceous time. Progressively older terrace gravels of the river lie north of the present channel and indicate a southward migration of the river channel, according to Howard (1960). Either the Yellowstone River maintained its course across the rising Cedar Creek anticline or the river was superimposed on the underlying structure from a higher ancestral surface. It is not known whether uplift and folding continued into Pliocene and Pleistocene time.

HYDROLOGY

HYDROLOGIC TERMS AND CONCEPTS

Any geologic formation, group of formations, or part of a formation that is saturated and is sufficiently permeable to transmit water readily under field conditions is known as an aquifer. The permeability of an aquifer is a consequence of the interconnection of interstices, which allows the movement of water. Common aquifers include gravel, sand, sandstone, or mixtures of sand and gravel.

Any geologic formation that is not sufficiently permeable to transmit water readily under field conditions is known as an aquiclude. The low permeability of an aquiclude is due to the molecular attraction in small interstices, poor particle-size sorting, or the lack of interconnection between interstices. Common aquicludes include clay and shale. Aquicludes that are adjacent to aquifers tend to confine the flow in the aquifer.

Ground water is under water-table conditions if it occurs in an aquifer that is not confined above. The water table is that surface within the zone of saturation at which the pressure is atmospheric. A map that shows the altitude of the water table is known as a water table map.

Ground water is under artesian conditions if it occurs in an aquifer that is confined above and the pressure in the aquifer is greater than atmospheric pressure. Thus if a tightly cased well is drilled into an artesian aquifer, the water will rise in the well above the top of the aquifer. The rise represents the head in the aquifer at the well.

The piezometric surface of an artesian aquifer is an imaginary surface that coincides with the head throughout the aquifer. If the piezometric surface of an artesian aquifer is above the land surface, a flowing artesian well could be constructed. A map that shows the altitude of the piezometric surface is known as a piezometric map.

Addition of water to an aquifer is known as recharge. An aquifer may be recharged by precipitation, streams, lakes, or surface reservoirs where the aquifer is exposed and not completely saturated.

Loss of ground water from an aquifer is known as discharge. Water may be discharged from an aquifer where it is exposed and is under sufficient hydrostatic pressure to flow at the surface, as into streams, lakes, or oceans. Other types of discharge include springs, pumped or flowing wells, evaporation, and transpiration.

The storage and transmissive properties of aquifers commonly are estimated by measurement of the aquifer constants, which are defined below. The coefficient of storage, S, of an aquifer is the volume of water it releases or takes into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface. The coefficient of storage is a dimensionless constant because it is expressed as $L^3/L^2/L$ where L is a unit of length. When recharge to an aquifer exceeds discharge, an increase in stored water occurs; when discharge from an aquifer exceeds recharge, a decrease in stored water occurs.

The storage coefficient of a water-table aquifer is relatively large compared to that of an artesian aquifer. In a water-table aquifer any water released from or taken into storage involves mostly gravity drainage or filling in the zone through which the water table moves. Conversely in the artesian aquifer any water released from or taken into storage does not involve dewatering or filling of the aquifer. Changes in artesian storage are attributed to the compressibility of the aquifer material and the water. Storage coefficients of water-table aquifers range from about 0.05 to 0.30; storage coefficients of artesian aquifers range from about 0.00001 to 0.001.

The coefficient of permeability as used by the Geological Survey is the flow of water in the aquifer in gallons per day through a cross-sectional area of one square foot under a hydraulic gradient of one foot per foot. Therefore, the coefficient of permeability has the dimension of gal./day/ft^2.

In hydrology, the ease of flow through an aquifer is also expressed as T, the coefficient of transmissibility. The coefficient of transmissibility as used by the Geological Survey is the flow of water in the aquifer in gallons per day through a vertical cross-sectional area one foot wide, with a height equal to the saturated thickness of the aquifer, under a hydraulic gradient of one foot per foot. It has the dimension of gal./day/ft (gpd/ft). The coefficient of transmissibility is equal to the coefficient of permeability multiplied by the saturated thickness of the aquifer. Therefore, transmissibility is of more value for estimating the potential yield of an aquifer than is permeability, which does not consider thickness.

The specific capacity of a well as used by the Geological Survey is the yield in gallons per minute divided by the head change in feet at the well and has the dimension of gallons/minute/foot of drawdown. The specific capacity of a well is not a constant but varies with the amount of discharge, the time since discharge began, the individual well construction, and the aquifer transmissibility.

In hydraulics, pressure is commonly expressed as either force per unit area or head. The relation between these two methods of expression is

$$p = h\gamma$$

where p is pressure, h is head, and γ is the specific weight of the fluid (for water at normal temperatures γ is 62.4 lb./ft.^{3}). If p is expressed in lb./in.^{2} and h in feet of water, the relation becomes, dimensionally

$$\text{lb./in}^2 = (\text{ft.})\ (\text{lb./ft.}^3)\ (\text{ft.}^2/\text{in.}^2) \text{ or}$$
$$p = h\ (62.4/144)$$
$$p = 0.433\ h$$

WELL INFORMATION

Statistics were gathered on 123 wells to learn more about the aquifers in the area. Most of the wells inventoried are deep wells that penetrate the aquifer in the Fox Hills and basal part of the Hell Creek. There are hundreds of shallower wells in the area but only a few were inventoried. The data collected include well location, well depth, method of completion, driller's log, yield, depth to water, head of flowing wells, and any other information necessary for the investigation.

The well data are listed in Table 1 (appendix). The well locations are plotted on Plates 1 and 2 (in pocket) with information about well depth and head.

In this report, all water wells are numbered according to their location within the land subdivisions of the Bureau of Land Management survey of the area (Fig. 4). The well number is composed of the township number, the range number, the section number, and lowercase letters that indicate the subdivision of the section in which the well is located. The first letter denotes the quarter section and the second letter denotes the quarter-quarter section within the preceding subdivision. The letters are assigned in a counterclockwise direction beginning in the northeast quarter

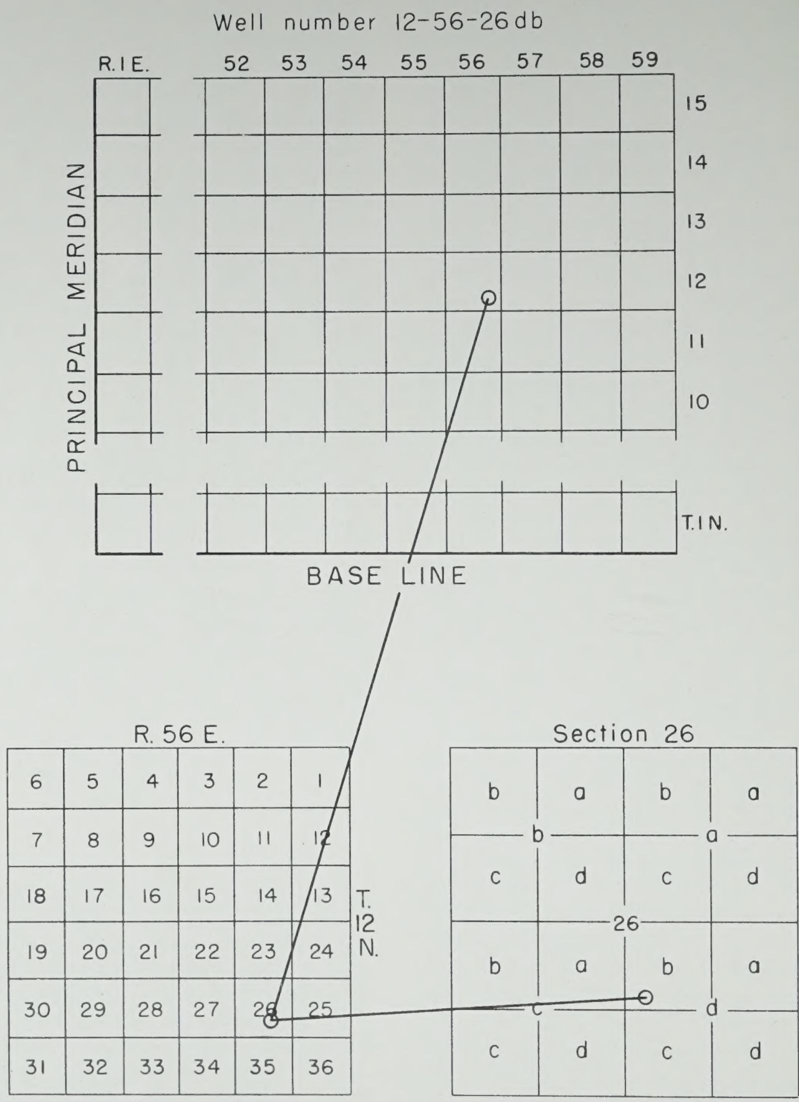

Figure 4.—Sketch showing well-numbering system.

of the section or quarter-quarter section. When two or more wells are located within a quarter-quarter section, the wells are numbered serially according to the order in which they were inventoried.

The altitude of the land surface at each well was determined for use in conjunction with the structure contour map and for the preparation of the piezometric map. The altitudes were carefully determined with a sensitive altimeter and corrections were made for diurnal variations in barometric pressure and air temperature. Bench marks are not abundant in the area but oil-well altitudes provided by the Basin Survey Company, Glendive, Montana, added enough points for adequate control. The altitudes probably are accurate within 10 feet.

AQUIFER DESCRIPTION

The aquifer in the Fox Hills and basal part of the Hell Creek is a sandy unit, which is variable in thickness but extensive throughout the area. Driller's logs indicate sandstone, sandy shale, and silty sandstone at depth, and it is difficult to assign an average thickness to the relatively permeable beds. Erdmann and Larsen (1934) measured 250 feet of sandstone in exposures near Glendive, but this figure cannot be taken as representative.

A better method of determining aquifer thickness is by the use of gamma-ray logs. The logs are prepared by lowering a scintillation counter down the well and measuring the variation of gamma-ray activity with depth. The gamma rays are emitted by potassium and decay products of uranium and thorium, all of which generally are more abundant in shale than in sandstone. Gamma-ray logs were obtained in four industrial wells in the area, and they all show the sandstone in the Fox Hills and basal part of the Hell Creek to be the thickest continuous aquifer. Thin erratic permeable beds higher in the section represent the aquifers in the upper part of the Hell Creek and in the Fort Union. The four gamma-ray logs indicate the following thicknesses for the aquifer of the Fox Hills and basal part of the Hell Creek:

Well	Thickness
11-57 -6cc	150 feet
12-56-34da	190 feet
12-56-25cb	280 feet
12-56-23cc	480 feet

Athough these measurements are all from one general area, they indicate that the thickness of the aquifer may be as great as 480 feet. Accordingly, in this report any water well which penetrates sandstone within 500 feet of the known base of the Fox Hills Sandstone is regarded as completed in the aquifer of the Fox Hills and basal part of the Hell Creek.

On Plate 1, the upper figure by the well symbol represents the altitude of the land surface at the well. The lower figure represents the altitude of the bottom of the well, which was computed by subtracting the well depth from the altitude of the land surface. The altitude of the bottom of the well is then compared with the local structure contour (or interpolated reading between two contours). For instance, well 12-55-22bc has a land surface altitude of 2,336 feet, a depth of 860 feet, and therefore, a bottom-of-well altitude of 1,476 feet. The altitude of the base of the Fox Hills Sandstone is interpolated as being about 1,180 feet at the well site. This well is completed 296 feet above the base of the Fox Hills and is, therefore, in the aquifer of the Fox Hills and basal part of the Hell Creek.

The information on Plate 1 can be used to compute drilling depth to the aquifer of the Fox Hills and basal part of the Hell Creek if the land surface altitude at the proposed well site is known. The difference between the land surface altitude and the structural contour altitude is the approximate drilling depth to the bottom of the Fox Hills Sandstone.

PIEZOMETRIC SURFACE OF AQUIFER IN FOX HILLS AND HELL CREEK FORMATIONS

A piezometric map shows the distribution of potential hydraulic energy in the aquifer, and from it many important deductions can be made regarding the recharge, movement, and discharge of ground water.

The piezometric surface of the aquifer was determined by relating the head in feet of water to mean sea level at selected wells completed in the aquifer (Pl. 2). For nonflowing wells, the measured depth of water below land surface was subtracted from the land surface altitude. For flowing artesian wells, (1) the flow was shut off for several hours to allow the pressure to recover, (2) the head at land surface was measured with an ink-well mercury gage (Jacob and Lohman, 1952) calibrated to read directly in feet of water, and (3) the measured head was added to the altitude of the land surface. Thus, only static heads were

recorded, all heads are referred to the same datum, and the piezometric contours were drawn by contouring about the control points. Care was taken to avoid the effects of nearby pumping or flowing wells. A few wells completed in the upper part of the Hell Creek or in the Fort Union are included on Plate 2 for comparison, but they were not used in contouring.

The figure by the well symbol on Plate 2 represents the altitude of the head and can be used in conjunction with the land surface altitudes on Plate 1 to determine whether the head is above or below the land surface. If the head shown on Plate 2 is higher than the land surface altitude shown on Plate 1, the well is a flowing artesian well and the difference between the two altitudes is the static head in feet of water above the land surface. If the head shown on Plate 2 is lower than the land surface altitude shown on Plate 1, the well is a nonflowing artesian well or a water-table well (in the outcrop) and the difference between the two altitudes is the depth to water below the land surface.

The information on Plate 2 can be used to predict whether a flowing artesian well can be obtained from the aquifer in the Fox Hills and basal part of the Hell Creek at a certain location. If the value of head is greater than the measured land-surface altitude, a flowing well will result when the aquifer is penetrated. If the value of head is less than the land-surface altitude, the difference of the two altitudes is the depth to water below land surface in the well. The two conditions are illustrated in Figure 5 with the geologic structure in cross section. Figure 6 shows the relation between the head and the initial yield for several flowing wells in the area. This relation expressed in gallons per minute per foot of drawdown is called the specific capacity of the well. Although differences in aquifer transmissibility, well discharge, and well construction result in a lack of linearity of the plot, a rough estimate of the yield of a well can be made from the static head. (See flow tests in appendix.)

The piezometric contours on Plate 2 probably are accurate within 10 feet in areas with adequate control points, but may be in error as much as 25 feet where there are few wells. Contours were not drawn on the eastern flank of the anticline, because too few reliable points on the piezometric surface are available.

OPERATION OF HYDROLOGIC SYSTEM

RECHARGE

AQUIFER IN FOX HILLS SANDSTONE AND BASAL PART OF HELL CREEK FORMATION

Plate 2 suggests that the main recharge area for the western flank of the anticline is on the northern flank of the Black Hills uplift where there are wide exposures of the aquifer at a relatively high altitude (Fig. 1). Another potential recharge area is the outcrop of the aquifer along the western flank of the anticline. There may be

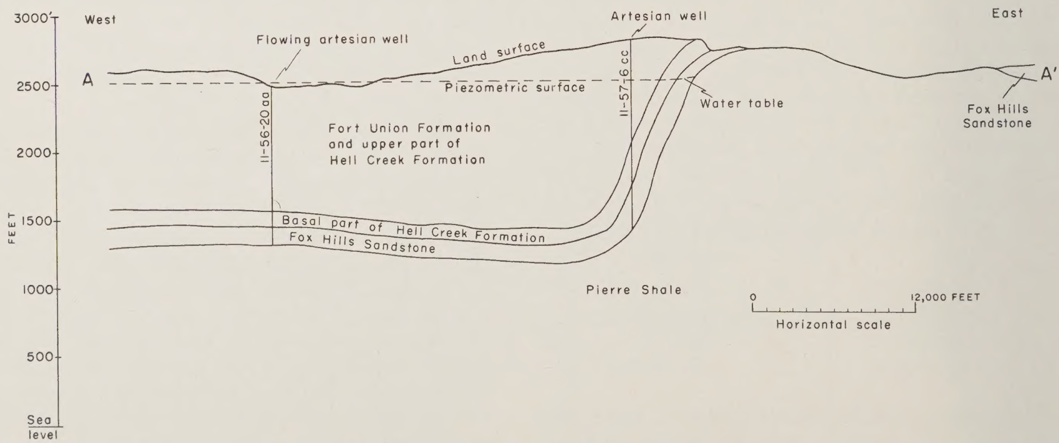

Figure 5.—Generalized cross section along AA' on Plate 1.

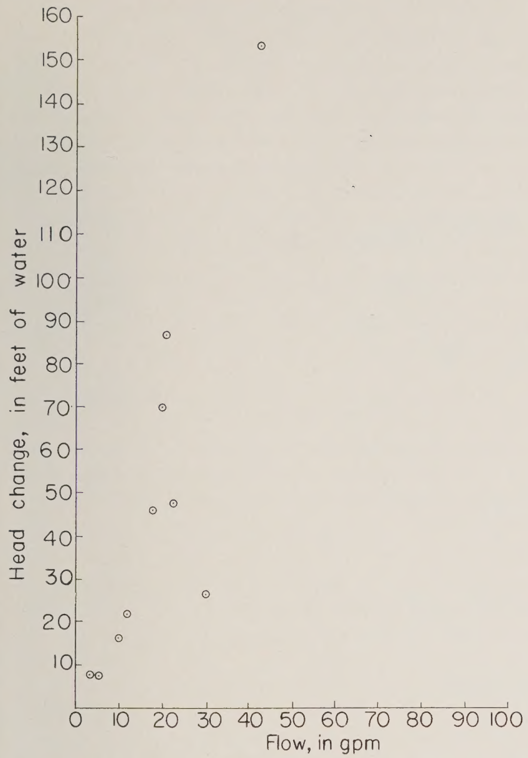

Figure 6.—Head change and initial yield for flowing wells completed in aquifer in Fox Hills Sandstone and basal part of Hell Creek Formation.

some recharge in T. 12 N., R. 56 E., where exposures of the Fox Hills Sandstone are more extensive than elsewhere along the western flank of the anticline. The configuration of the piezometric contours in the area is also affected by many flowing and pumped wells, some of which have been used for many years. From the piezometric map it is difficult to assess the amount of recharge along the narrow outcrop, because control is not adequate for the determination of the slight contour deflections that would be expected.

Another method of evaluating recharge to the outcrop is by studying the hydrographs of wells in the outcrop. Figure 7 shows the hydrographs of six wells in the outcrop and concurrent precipitation along the anticline. Well 7-59-2cd is the only well in which the water level responded significantly to greater than normal precipitation within the period of record shown. Very little recharge would be expected in the outcrop area, because the exposure area of the aquifer is small, the precipitation is light, and evaporation is aided by low relative humidity, moderate wind movement, and hot summers. The aquifer permeability is low, and therefore the downward percolation of precipitation would be small and capillary rise above the water table would be large. In the northern part of the anticline, water accumulates in undrained depressions in the outcrop, but, the aquifer is not saturated below the ponds, because they have been partly sealed with fine sediment washed from nearby exposures. Thus, most of the ponded water is lost by evaporation.

Recharge of the aquifer on the eastern flank of the anticline probably occurs in the broad exposures east of Baker. The entire outcrop of the aquifer along the eastern flank may be an important recharge area because of the relatively large area of outcrop.

UPPER PART OF HELL CREEK FORMATION AND FORT UNION FORMATION

Recharge of the aquifers of the upper part of the Hell Creek Formation and the Fort Union Formation was not investigated. Cabin Creek loses a large part of its flow before it reaches the Yellowstone River, and evaporation alone cannot account for the loss. Thus, recharge to the Fort Union Formation probably occurs through sandstone beds exposed in its extensive outcrop area. The sandstone beds probably receive recharge from precipitation as well as from influent streams. Presumably the exposed sandstone beds are interconnected with deeper aquifers in the upper part of the Hell Creek Formation and in the Fort Union Formation, and thus both formations are recharged. Also, the aquifer in the Fox Hills and basal part of the Hell Creek may be in hydraulic connection with the aquifers of the upper part of the Hell Creek in certain places.

MOVEMENT

Ground water always moves down gradient because it flows from one energy state to a lower energy state and in so doing dissipates energy in the form of friction in the aquifer. The movement occurs perpendicular to the piezometric contours. Therefore, the general direction of groundwater movement in the aquifer in the Fox Hills and basal part of the Hell Creek is toward the northwest and approximately parallel to the trend

of the anticline (Pl. 2). The velocity of ground-water movement would be extremely low, probably less than 4 feet per year, in this aquifer because of the low regional hydraulic gradient and low permeability.

DISCHARGE

ACQUIFER IN FOX HILLS SANDSTONE AND BASAL PART OF HELL CREEK FORMATION

Ground water in the aquifer in the Fox Hills Sandstone and basal part of the Hell Creek Formation is discharged to the Yellowstone River as shown by the steep hydraulic gradient in T. 13 N., R. 54 E. (Pl. 2). The river crosses the outcrop a little farther downstream.

Ground water in this aquifer also is discharged where Cabin Creek crosses the outcrop in sec 27, T. 11 N., R. 57 E. Springs issuing from the aquifer feed Cabin Creek and add considerably to its flow.

Nearly every town in the area obtains its municipal supply from the aquifer. The towns of Baker, Plevna, Mildred, Ismay, and Willard would have great difficulty in obtaining a suitable water supply from any other source. There are hundreds of private domestic and livestock wells completed in the aquifer. Many wells were drilled along O'Fallon and Cabin Creeks because flowing wells can be obtained in these topographically low areas. Industrial wells use water from the aquifer for secondary recovery of petroleum, petroleum treatment, and associated processes. The amounts and effects of proposed withdrawals will be discussed in a later section.

UPPER PART OF HELL CREEK FORMATION AND FORT UNION FORMATION

The discharge from aquifers in the upper part of the Hell Creek Formation and in the Fort Union Formation was not investigated, but it is

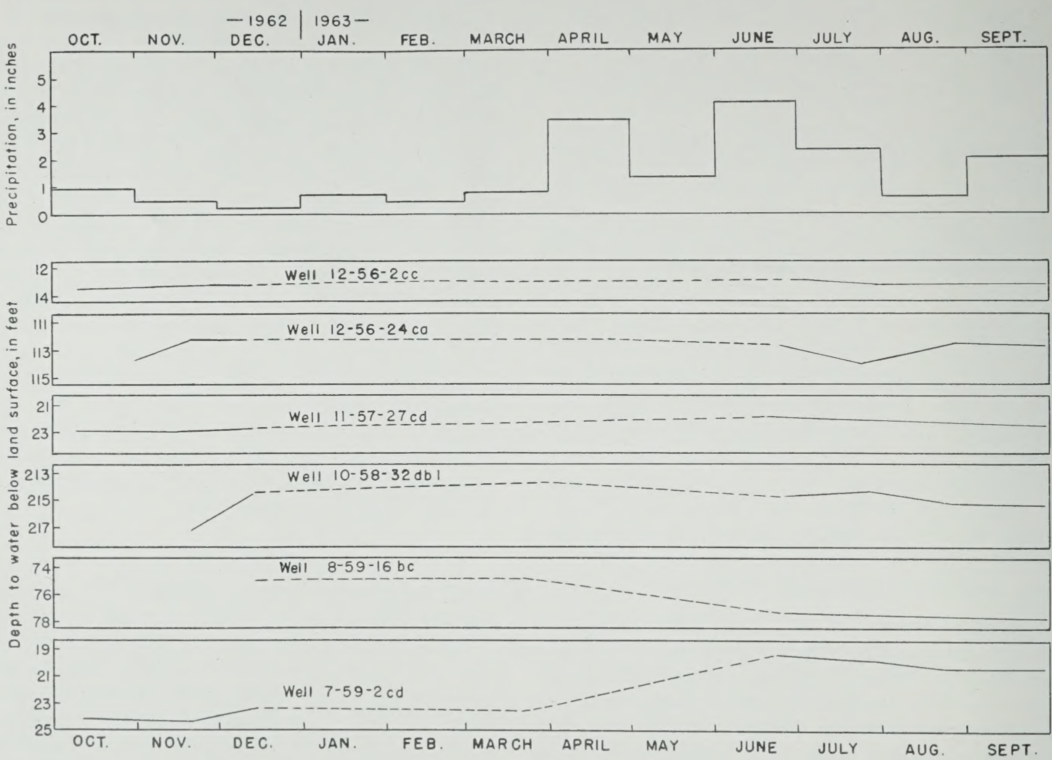

Figure 7.—Mean monthly precipitation at Glendive, Plevna, and 10 miles west of Carlyle; and hydrographs of water levels in selected wells.

likely that they discharge naturally into the Yellowstone River. A few springs issue from the aquifers, especially where the surface relief is great and sandstone beds are exposed. Many private livestock and domestic wells are completed in the aquifers; many of these wells are artesian, and some have moderate flows.

CHEMICAL QUALITY OF GROUND WATER IN HYDROLOGIC SYSTEM

GEOCHEMICAL TERMS AND CONCEPTS

Pure water is a chemical compound of oxygen and hydrogen, having the molecular formula H_2O. The configuration of the molucule explains the high dielectric constant and dipole moment of water; the two hydrogens lie on one side of the larger oxygen so that there is a separation of the centers of positive and negative charges.

The dipole molecules of water are linked together with hydrogen bonds and it is this associated structure of the liquid that causes it to have remarkable properties. Water has unexpected high values for specific heat, boiling point, melting point, latent heats of fusion and vaporization, and surface tension.

Water is unequaled as a wide-range solvent for gases, liquids, and solids because many instantaneous reactions take place that involve water as one of the reactants. Many ionic substances and some covalent substances are dissolved in water because the water dipoles weaken the bonds until they rupture, and hydrated ions are formed. In this interpenetration, some of the hydrogen bonds of water must also be ruptured. Some normally insoluble substances may be converted to soluble ions or molecules as a result of certain acid-base reactions. Some of these reactions involve water, which may act as either an acid or a base. Oxidizing or reducing agents in aqueous solution may change the oxidation state and solubility of solids or dissolved solids with which they come in contact.

Ion exchange is a natural process in which the dissolved mineral concentration of water may be changed by the substitution of ions in the water for ions in solid materials through which the water percolates. Clay minerals, particularly those of the montmorillonite group, are effective exchangers. One common ion-exchange process tends to exchange dissolved calcium and magnesium in ground water for sodium in clay minerals, thus enriching the clay in calcium and magnesium and enriching the water in sodium. The processes by which ground water obtains its chemical characteristics are thus a complicated series of reactions that dissolve gases and solids from the atmosphere, soil, and aquifer through which the water passes.

Ground-water samples were collected from wells on the western flank of the anticline. The results of the analyses are given in Table 2 with other analyses obtained from industrial sources. For a more detailed discussion of the chemistry of natural waters the reader is referred to a paper by Hem (1959).

In the chemical analyses shown in Table 2, chemical constitutents are presented in parts per million by weight, a ratio between the weight of the chemical constituent and the weight of the sample. For special purposes, analyses may be reported in equivalents per million, which are computed by dividing parts per million by the combining weight of the ion.

The concentration of dissolved solids in a water sample is determined by evaporating a measured amount of the sample and weighing the residue thus obtained. The figure for total dissolved solids includes measurement of certain constituents that are not measured in the partial chemical analysis and is subject to certain errors that differ from those in the partial chemical analysis. The sum of individual chemical constitutents, therefore, need not be exactly equal to the total dissolved solids measurement, but one serves as a rough check on the other.

Hardness is computed as if it were all due to calcium carbonate. Total hardness represents the effect of all substances that react with soap. Calcium-magnesium hardness represents values computed from the concentrations of these two ions alone. Any hardness in excess of that due to carbonate and bicarbonate in the water is known as noncarbonate hardness.

Percent sodium is computed from the formula

$$\text{Percent sodium} = \frac{100\ (\text{Na} + \text{K})}{(\text{Ca} + \text{Mg} + \text{Na} + \text{K})}$$

in which the concentrations are expressed in equivalents per million. If the percent sodium is more than 50, the water is of doubtful value for irrigation, because sodium enrichment relative to calcium and magnesium tends to cause the replacement of calcium and magnesium in the soil

TABLE 2.—ANALYSES OF WATER FROM AQUIFERS ON WESTERN FLANK

(Analyses in parts per million, except as indicated)

Well location	Date of collection	Depth of well (feet)	Temperature (°F)	Silica (SiO_2)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)
								Fox Hills Sandstone and basal			
5-56-17dd	9- 4-63	646	56	14	0.08	0.05	0.3	0.6	247	0.8	522
* 7-59-11cb	1-29-62						Tr	Tr	421		525
8-58-30bd	8-30-63	1,176	64	12	.01	.01	1.7	.2	365	1.0	575
9-55-27bb	8-30-63	1,100	60	12	.06	.00	1.1	.2	318	0.8	654
*10-58-18cd	1-16-62	395					9	4	765		1,098
*10-58-32db1	10-27-58	463					13	5	877		1,049
*10-58-32db2	4-26-61	497					8	3	840		793
11-54-29ca	8-30-63	865	54	11	.02	.00	1.8	.4	315	.8	645
*11-55- 2ac	1-29-62	1,110					Tr	Tr	376		476
*11-57-17bc	1-29-62	1,190					Tr	Tr	375		573
*11-57-21cb2	5-19-61	710					5	1	507		293
*11-57-21cb3	12- 2-57	1,230					12	0	581	0	607
*11-57-32bb	1-29-62	980					Tr	Tr	443		683
*12-55-15bc	1-29-62	980					2	1	387		561
*12-55-16db	1-29-62	920					Tr	Tr	376		573
*12-55-20dc	1-29-62	1,185					Tr	Tr	372		549
*12-55-21dd	1-29-62	813					Tr	Tr	457		817
*12-55-22bc	1-29-62	860					6	1	585		1,110
*12-56-10ac	10-27-58	1,170					13	3	688		1,013
*12-56-23dc	5- 7-52	1,185					0	0	462		970
14-54-34cb	8-28-63	816	63	13	.04	.00	1.2	.2	340	.8	706
									Hell Creek and Fort		
6-56-31bc	9- 4-63	320	63	12	.03	.00	.6	.4	260	.8	468
9-55- 5bc	8-30-63	360	55	8.8	.04	.00	2.6	2.3	620	1.7	936
11-56- 2ca	8-28-63	246	53	14	.01	.01	140	124	187	6.8	523
12-55-35ac	8-30-63	180	50	11	.14	.09	4.2	1.3	480	1.6	558
13-55-18dc	8-28-63	50	50	11	.00	.00	190	172	106	8.1	413

*Analysis by Shell Oil Co.

OF CEDAR CREEK ANTICLINE, MONTANA

Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Dissolved solids (residue at 180°C)	Hardness as $CaCO_3$		Percent sodium	Sodium adsorption ratio	Specific conductance (micromhos at 25°C)	pH
							Calcium magnesium	Noncarbonate				
part of Hell Creek Formation												
00	103	2.9	0.6	0.2	0.22	636	3	0	99	62	997	8.0
108	272	16					Tr				1,560	8.4
50	165	38	.9	.2	.56	933	5	0	99	71	1,450	8.4
0	126	14	1.4	.1	.42	816	4	0	99	69	1,260	8.2
	749	16					39		98	53	2,940	7.6
60	942	14							97	52	3,050	8.7
108	934	40					33		99	65	3,400	8.3
22	85	16	1.5	.1	.51	783	6	0	99	56	1,240	8.6
132	156	32					Tr				1,460	8.4
84	171	20									1,340	8.4
72	704	20					17		99	54	2,060	8.7
0	720	34					30		98	46	2,420	8.0
108	197	14					Tr				1,590	8.4
120	143	30					9		99	56	1,370	8.5
132	82	30					Tr				1,380	8.5
120	120	24					Tr				1,350	8.5
132	70	22					Tr				1,390	8.4
156	91	20					19		99	58	1,920	8.4
72	542	20							97	45	2,410	9.0
0	163	28					0				1,360	8.0
33	54	23	2.5	.1	.64	829	4	0	99	74	1,300	8.5
Union Formations												
14	126	6.2	.4	.1	.23	662	3	0	99	65	1,030	8.4
98	356	13	4.3	.1	.72	1,600	16	0	99	67	2,390	8.6
0	778	3.8	.0	1.2	.18	1,660	861	432	32	2.8	2,020	7.8
0	565	12	.6	.4	.24	1,390	16	0	98	52	2,050	8.1
0	1,000	3.0	.0	.0	.16	1,850	1,180	841	16	1.3	2,130	7.8

by sodium. A soil that is enriched in exchangeable sodium becomes deflocculated, and drainage is impaired.

The sodium-adsorption ratio (SAR) of a water sample is more indicative of the extent to which sodium is adsorbed in the soil than is percent sodium. SAR is computed from the formula

$$SAR = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}}$$

in which all concentrations are expressed in equivalents per million. SAR does not include the effects of potassium, because the adsorption of potassium ions by the soil is not harmful.

The chemical quality of a water sample may be estimated by the determination of the specific conductance of the samples. Because the electric conductance of water varies with the total solids dissolved in the water, a high specific conductance indicates a high dissolved-solids concentration. A specific-conductance determination is only a semi-quantitative estimate of the total dissolved solids in the sample and gives no clue as to the specific constituents that are present. For most water samples, the total dissolved solids, in parts per million, is equal to 55 to 75 percent of the specific conductance as expressed in micromhos per centimeter at 25°C. Thus, a water sample having a specific conductance of 2,000 micromhos could be expected to have a concentration of 1,100 to 1,500 parts per million total dissolved solids.

The pH of a solution is a measure of the acidity or alkalinity, pH 7 being the neutral point. As the pH decreases below 7, the solution becomes progressively more acidic; as the pH increases above 7, the solution becomes progressively more alkaline. The pH is the logarithm of the reciprocal of the hydrogen ion concentration, and a unit change in the pH represents a change by a factor of ten in the hydrogen ion concentration.

SIGNIFICANCE AND INTERPRETATION

The analyses in Table 2 show that the most abundant ions are sodium, bicarbonate, sulfate, carbonate, and chloride. The ions are probably dissolved from evaporite minerals as the ground water moves slowly through the aquifer.

The lack of significant concentrations of calcium and magnesium ions in all but two samples shows that the ground water is very soft. Calcium and magnesium presumably were dissolved with other ions but ion-exchange processes removed them from solution in exchange for sodium. Renick (1925) and Riffenburg (1925) noted a progressive increase in sodium and decrease in calcium and magnesium with increasing well depth in the area. They attributed this relation to ion-exchange processes, which undoubtedly have their effect.

APPLICABILITY

Chemical standards for drinking water, prepared by the U. S. Public Health Service (1962), are shown below for the ions that were determined in the chemical analyses of water samples from the study area.

Chemical constituent	Maximum recommended concentration (ppm)
Chloride (Cl)	250
Fluoride (F)	1.5*
Iron (Fe)	0.3
Manganese (Mn)	0.05
Nitrate (NO_3)	45
Sulfate (SO_4)	250
Total dissolved solids	500

* for an annual average maximum daily air temperature of 53.8°-58.3°F.

All samples listed in Table 2 exceed the standard shown for dissolved solids, and some have concentrations of sulfate, fluoride, and magnesium that exceed the recommended standards. The standards for chloride, sulfate, and dissolved solids are based to a large extent on recommended concentrations for water used by interstate travelers. In general, the water is suitable for domestic and livestock use.

The high values for percent sodium and sodium-adsorption ratio of the ground water preclude the possibility of using it for irrigation. There would also be a high salinity hazard because of the total dissolved solids concentration of the ground water.

EFFECT OF INDUSTRIAL USE OF GROUND WATER ON HYDROLOGIC SYSTEM

Pumping water from an aquifer will affect the head in the aquifer, and the effect can be determined if the following are known: (1) the rates and points of withdrawal; (2) average values for

the coefficients of storage and transmissibility; (3) the areal extent of the aquifer, and (4) the hydraulic controls that affect drawdown or recharge in the perimeter of the aquifer.

AMOUNT TO BE USED AND POINTS OF WITHDRAWAL

Industrial withdrawals of water from the aquifer in the Fox Hills and basal part of the Hell Creek for use in the secondary recovery of petroleum, petroleum treatment, and related processes are planned for a 21-year period beginning in 1964. During this time, about 4 billion gallons (an average rate of 360 gpm) will be withdrawn from the aquifer. The water will be produced from industrial wells 11-57-21cb2, 11-57-17bc, 11-57-6cc and 12-56-23cc.

Owing to technical problems in the secondary recovery process, predictions of future water requirements are difficult. Salt water is produced with the oil and is injected with the fresh water. The quantity of salt water produced is expected to increase with time, and if so the requirements for fresh water will decrease. The quantity of fresh water that will be required from each industrial well, based upon realistic estimates made in 1962 by the industrial users, is shown in Figure 8. Actual withdrawals from the wells through the fall of 1964 were about 60 percent of the quantity originally estimated.

All the water that will be withdrawn from the aquifer for industrial use will be withdrawn from the western flank of the anticline. There will be no effect on the piezometric surface of the aquifer on the eastern flank, because the aquifer is discontinuous to the east.

AQUIFER CONSTANTS OF FOX HILLS AND BASAL PART OF HELL CREEK FORMATIONS

Thirty aquifer tests were made using wells completed in the Fox Hills and basal part of the Hell Creek Formations on the western flank of the anticline in order to determine values of the coefficients of transmissibility and storage. The tests were of three types: (1) drawdown tests; (2) recovery tests; and (3) flow tests. All test data, graphical plots of data, and available well logs collected in the investigation are included in the appendix to this report. For a discussion of aquifer tests and references to original papers, the reader is referred to the paper by Ferris and others (1962).

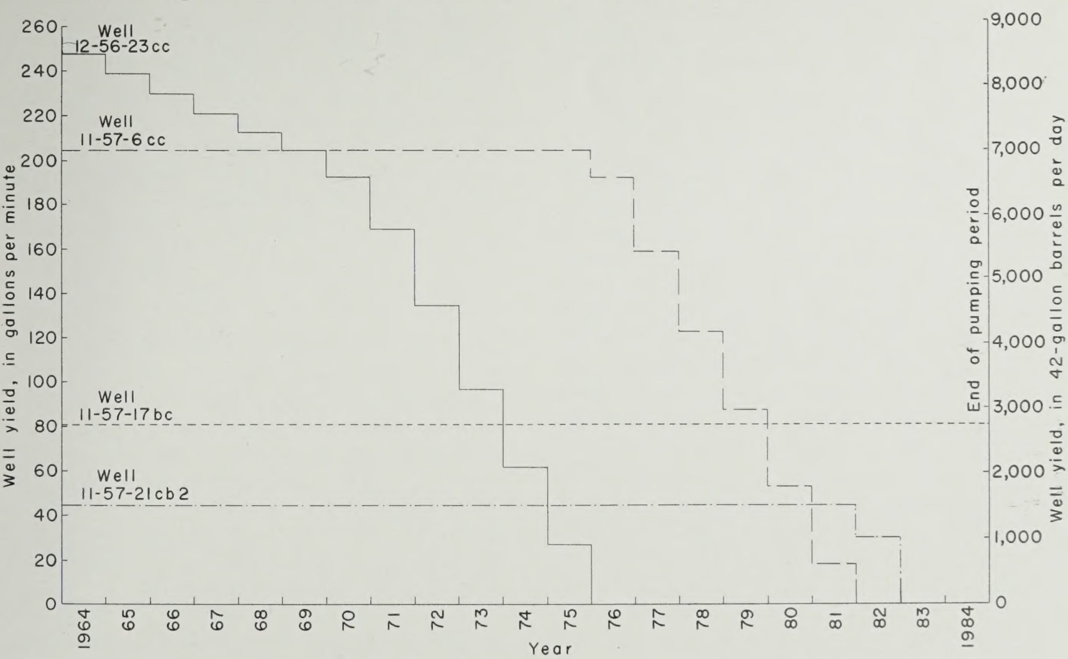

Figure 8.—Proposed industrial withdrawal of ground water from aquifer in Fox Hills Sandstone and basal part of Hell Creek Formation.

Drawdown tests are performed by pumping a well at a constant rate so that a cone of depression develops in the head of the aquifer. The development of a cone of depression near a pumped well is shown schematically in Figure 9. The cone grows rapidly at first but its rate of growth gradually declines. In a drawdown test the decline of head at various time intervals is measured in observation wells that are within the cone of depression.

The shape of the cone of depression in an artesian aquifer of infinite extent is defined by the Theis nonequilibrium equations

$$s = \frac{114.6\ Q\ W(u)}{T} \qquad (1)$$

$$u = \frac{1.87\ r^2\ S}{Tt} \qquad (2)$$

where s is the drawdown of the water level, in feet, at an observation well; Q is the constant discharge of the pumped well, in gallons per minute; T is the transmissibility of the aquifer, in gallons per day per foot; r is the distance from the pumped well to the observation well, in feet; S is the storage coefficient of the aquifer; t is the time, in days, that has elapsed since pumping began; and W(u) is the well function of u. The relation between W(u) and values of u is determined by a type curve or table (Wenzel, 1942). By superimposing a plot of the drawdown data collected at each observation well on the type curve of W(u) versus u, it is possible to determine values of T and S using equations (1) and (2). A drawdown test is a method of determining the only two unknowns in equations (1) and (2), T and S. If the drawdown test is of sufficient duration to give good estimates of T and S, then it is possible to compute the drawdown for any value of r, t, or Q in an aquifer. Aquifer tests 3 and 9 are drawdown tests of this type. (See appendix.) Aquifer constants were not computed for aquifer test 9 because the observation well did not completely penetrate the aquifer and the test was therefore invalid. The drawdown measured in this well will be referred to in a later section, however.

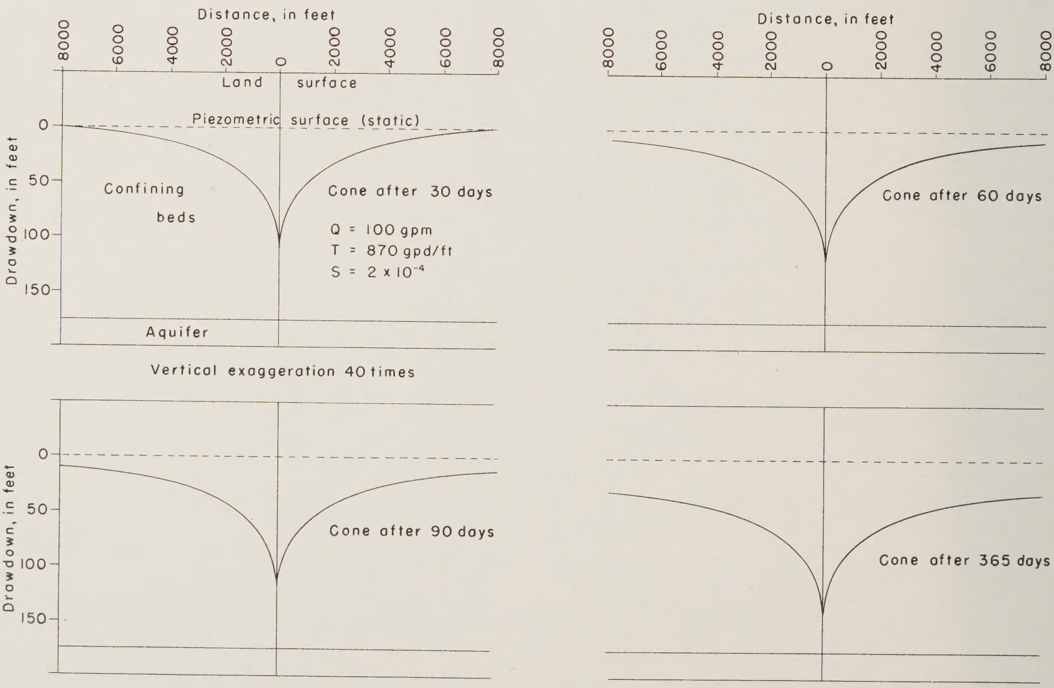

Figure 9.—Schematic diagrams showing development of cone of depression.

A drawdown test can be made in which drawdown is measured only in the pumped well. A single-well drawdown test is made if there is no nearby observation well. The disadvantages of the test are that the drawdown is sensitive to slight variations in discharge, and the coefficient of storage cannot be determined accurately. The value of T is determined by plotting s versus t on semilogarithmic paper and using the Jacob (1950) nonequilibrium formula

$$T = \frac{264Q}{\Delta s} \qquad (3)$$

where Δs is the change in drawdown per log cycle of t. This approximate formula is applicable in any pumping test only if u is less than 0.01. In equation (2) it can be seen that u will be small if r is small and t is large.

Single-well drawdown tests include tests 2, 12, 16, and 18. (See appendix.) Aquifer test 12 gave poor results, owing partly to variations in the discharge rate. Aquifer tests 12 and 18 indicated either a decrease in aquifer transmissibility or a hydrologic boundary in the vicinity of the pumped well.

In recovery tests utilizing a single well, the recovery of head was measured in the pumped well after discharge ceased. The disadvantages of single-well recovery tests are that the recovery measurements are very sensitive to leakage from the pump column after pump shutoff, and the coefficient of storage cannot be determined easily. The value of T is computed from a corollary to the Theis nonequilibrium formula

$$T = \frac{264Q}{\Delta s'} \qquad (4)$$

where s′ is the residual drawdown, the difference between the recovered presure head and the original static presure head. Values of s′ are plotted versus values of t/t′ on semilogarithmic paper, t being the time elapsed since pumping began and t′ being the time elapsed since pumping ceased. The term $\Delta s'$ in equation (4) is the change in residual drawdown per log cycle of t/t′. The function u must be less than 0.01 in order to apply equation (4), but this condition is easily met in the pumped well where r is very small.

Single-well recovery tests include tests 13, 17, and 19. (See appendix.) Recovery tests are usually performed after drawdown tests on the same wells, for comparison of the two methods. Any difficulties encountered during the drawdown tests also affect the recovery tests. The variable discharge during aquifer test 12 thus affected aquifer test 13 and made the recovery curve nonlinear. The shape of the curve for aquifer test 17 probably is due to leakage from the pump column during recovery, but the T values for the test are similar to the value determined in aquifer test 16. Aquifer test 19 was affected by the boundary or transmissibiilty change detected during aquifer test 18 and therefore gave erroneous results.

Recovery after pumping is stopped may also be measured in an observation well. Aquifer test 8 was made in this manner, but equation (4) could not be used because r was large and, therefore, u was greater than 0.01 during recovery. Equations (1) and (2) were used for test 8 because they are applicable for either drawdown or recovery measurements. In this analysis the discharge Q is replaced by an imaginary injection Q, which causes a recovery of the head in the aquifer. The pumping period prior to recovery was sufficiently long that the cone of depression had essentially stabilized, hence in the observation well during the recovery period there was no drawdown that was caused by prior pumping.

The third type of aquifer test, the flow test, was devised by Jacob and Lohman (1952) for determining values of T and S from a single flowing artesian well. The test is made by (1) shutting off flow for at least 18 hours to allow the head to recover; (2) measuring the static head with an ink-well mercury gage; (3) opening the well to allow maximum flow; (4) measuring the decline in flow at selected time intervals; and (5) recording the head at the well during flow. In the flow test, the drawdown at the well is constant and the discharge varies with time; in the drawdown test the discharge is held constant and the drawdown varies with time.

Values of $t/(r_w)^2$ are plotted versus values of s_w/Q on semilogarithmic paper, t being the elapsed time in minutes, r_w being the effective radius of the well in feet, and s_w being the constant drawdown at the well, in feet. The value of T is computed from the formula

$$T = \frac{264}{\Delta s_w/Q} \qquad (5)$$

where $\Delta s_w/Q$ is the change in s_w/Q per log cycle of $t/(r_w)^2$. The value of S is computed from the formula

$$S = \frac{2.1 \times 10^{-4}\, T\, (t/(r_w)^2)}{\log^{-1}_{10} \left[\dfrac{s_w/Q}{\Delta s_w/Q} \right]} \quad (6)$$

Equation (6) is solved by using values of T and $\Delta s_w/Q$ determined in equation (5) and values of s_w/Q and $t/(r_w)^2$ from any point on the curve. Flow tests include tests 4, 6, 10, 14, 20, 22, 24, 26, and 28. (See appendix.)

The values of T obtained from flow tests seem reasonable, but may be slightly high because of well completion techniques. Some drillers do not cement the casing from the surface to the top of the main aquifer, but insert a packer in the annular space outside the casing and just above the shallowest significant aquifer. With this technique the casing may be cemented only near the surface. Thus, the well may produce not only from the aquifer in the Fox Hills and basal part of the Hell Creek but also from aquifers in the upper part of the Hell Creek and in the Fort Union. Flow from the shallower aquifers, however, probably affects the measured transmissibility very little.

Many of the computed values of S are probably too small. Equation (6) shows that the computed value of S is inversely proportional to $(r_w)^2$. In computing values of S from equation (6) r_w was assumed to equal the radius of the drilled hole. That the effective well radius has been increased to some value greater than the nominal radius of the drilled hole seems probable because none of the flowing wells have well screens, the sandstone is poorly cemented, and some drillers report that newly drilled flowing wells yield sandy water for several days.

The flow-recovery test is made by measuring the recovery of head in the well with an ink-well mercury gage after the flow is shut off. The transmissibility is determined by plotting s′ versus t/t′ on semilogarithmic paper and using equation (4), or by plotting h′, the recovered head, versus t/t′ and using

$$T = \frac{264Q}{\Delta h'} \quad (7)$$

where $\Delta h'$ is the change in recovered head per

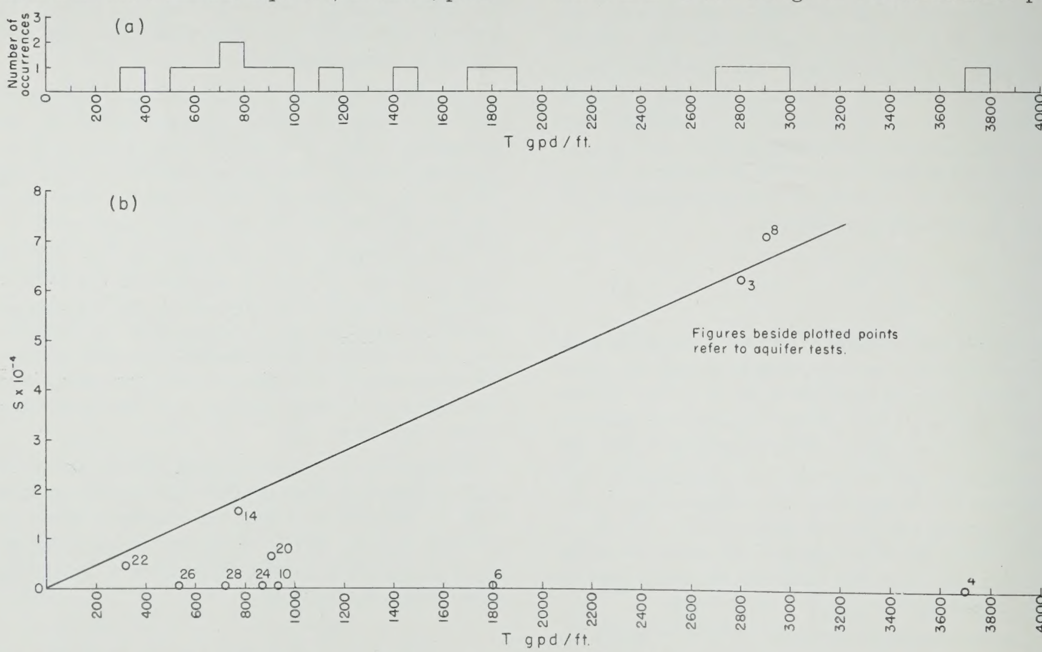

Figure 10a.—Histogram of values of transmissibility, T. 10b.—Relation between transmissibility, T, and coefficient of storage S.

TABLE 3.—SUMMARY OF VALUES FOR COEFFICIENTS OF TRANSMISSIBILITY AND STORAGE OBTAINED FROM AQUIFER TESTS ON FOX HILLS SANDSTONE AND BASAL PART OF HELL CREEK FORMATION ON WESTERN FLANK OF CEDAR CREEK ANTICLINE

Aquifer test number	Type of aquifer test	Well number	Transmissibility in gpd/ft	Coefficient of storage S	Comments
			Southern part		
1	Flow recovery	5-56-17dd	3,000		
2	Single well drawdown	7-59-14da	1,900		
3	Drawdown	7-59-11bd	2,800	6.2×10^{-4}	Observation well at 98 feet
4	Flow	8-56-27bc	3,700	2.4×10^{-11}	S value invalid
5	Flow recovery	8-56-27bc	4,800		Nonlinear recovery
6	Flow	9-55-27bb	1,800	5.6×10^{-14}	S value invalid
7	Flow recovery	9-55-27bb	1,000		
8	Recovery	10-58-32db2	2,900	7.1×10^{-4}	Observation well at 920 feet
		Mean T value = 2,600			
			Northern part		
9	Drawdown	10-58-18cd			Observation well at 670 feet Test invalid
10	Flow	11-56-20aa	940	2.2×10^{-6}	S value invalid
11	Flow recovery	11-56-20aa	1,000		Nonlinear recovery
12	Single well drawdown	11-57-6cc	2,500		T decrease or boundary indicated, Q erratic
13	Single well recovery	11-57-6cc	1,000		Nonlinear recovery
14	Flow	12-55-36dd	780	1.57×10^{-4}	
15	Flow recovery	12-55-36dd	950		Nonlinear recovery
16	Single well drawdown	12-56-25cb	620		
17	Single well recovery	12-56-25cb	890, 730		
18	Single well drawdown	12-56-23cc	2,400		T decrease or boundary indicated
19	Single well recovery	15-56-23cc	2,600		
20	Flow	12-56-19cd	910	6.3×10^{-5}	S value invalid
21	Flow recovery	12-56-19cd	1,400		
22	Flow	12-55-16db	320	4.6×10^{-5}	
23	Flow recovery	12-55-16db	370		
24	Flow	12-55-15bc	880	3.0×10^{-8}	S value invalid
25	Flow recovery	12-55-15bc	820		
26	Flow	12-55-8cc	530	1.1×10^{-7}	S value invalid
27	Flow recovery	12-55-8cc	580		
28	Flow	13-54-22ca	720	1.8×10^{-9}	S value invalid
29	Flow recovery	13-54-22ca	670		
30	Flow recovery	14-54-25bb	1,800		
		Mean T value = 870			

log cycle of t/t'. The discharge varies during the flow test and an average value of Q must be used in equation (4) or (7). The flow-recovery test can also be used on flowing wells that cannot be shut off for more than a few hours. If the well has been flowing for a long time, the present flow is nearly equal to the average flow. (See aquifer test 30 in appendix.)

Flow-recovery tests include tests 1, 5, 7, 11, 15, 21, 23, 25, 27, 29, and 30. (See appendix.) A flow-recovery test is usually made following a flow test. In general, the T values obtained by the two types of tests are comparable, but some of the flow recovery curves are nonlinear. The lack of linearity is probably caused by leakage from one aquifer to another during recovery or through pressure-sensitive leaks in the well casing.

The data collected from the aquifer tests are summarized in Table 3. The aquifer tests are numbered according to the location of the test wells, the test numbers increasing in a northerly direction. In Table 3 the values of T that are judged to be valid are underscored; none of the other T values were used in computations. Where more than one value of T was determined from different aquifer tests of the same well, the mean T value was chosen. There is a large range in the 15 values of T as shown in the histogram in Figure 10a.

The differences in transmissibility probably are due to variations in both aquifer thickness and permeability. The driller's logs, which are included in the appendix, indicate a variation in aquifer thickness but the interpretation of the logs is arbitrary, and only a semi-quantitative comparison between aquifer thickness and measured transmissibility is possible. The heterogeneity of the aquifer is apparent in the outcrop, where there are shale lenses and variations in sand size, sorting, and cementation. The aquifer permeability can be regarded as reasonably uniform, however, for the large volume of aquifer that will be affected by the industrial withdrawal of ground water. If the permeability is uniform in this broad sense, then the transmissibility depends only upon aquifer thickness.

Aquifer tests 1-8 were made in the southern part of the area, where the mean value of T was computed to be 2,600 gpd/ft. Aquifer tests 9-30 were made in the northern part of the area, where the mean value of T was computed to be 870 gpd/ft. The northern part of the area will be affected by the industrial withdrawals of ground water.

In Table 3 the storage coefficients determined from aquifer tests 3 and 8 are thought to be valid, but many of the values determined from flow tests may be in error, as previously discussed. Jacob (1950) has shown that the storage coefficient can be expressed as

$$S = \gamma_0 \, \theta \, m \left(\beta + \frac{\alpha}{\theta} \right) \tag{8}$$

where γ_0 is the specific weight of water at a stated reference temperature, θ is the porosity of the aquifer, m is the thickness of the aquifer, β is the compressibility of water, and α is the vertical compressibility of the solid skeleton of the aquifer. The terms γ_0 and β are constant at a given temperature, and S varies only with θ, α, and m. The aquifer porosity, θ, and the aquifer compressibility, α, can be considered uniform in the same sense that the aquifer permeability was considered uniform. Therefore, S and T vary mainly with the aquifer thickness, m. In Figure 10b, four of the plotted points confirm these assumptions and permit estimates of S that are based on the measured T values. In the southern part of the area where the mean T value is 2,600 gpd/ft, the corresponding S value is 6×10^{-4}; in the northern part of the area where the mean T value is 870 gpd/ft, the corresponding S value is 2×10^{-4}. In Table 3 the values of S that are judged to be valid are underscored.

A value of α can be computed from equation (8) by substitution of reasonable values of the other variables. Average values of S and m were determined from aquifer tests 3 and 8 and used with estimated or known values of the other variables as follows:

$S = 6.7 \times 10^{-4}$

$\gamma_0 = 3.61 \times 10^{-2}$ lb/in.^{3}

$\theta = 0.40$ (estimated)

m = 160 feet = 1,920 inches

$\beta = 3.3 \times 10^{-6}$ in.^{2}/lb.

The vertical compressibility of the solid skeleton of the aquifer computed from these values is 8.4×10^{-6} in^2/lb. The coefficient of storage of the aquifer is, for the most part, due to the compressibility of the aquifer skeleton, because $\dfrac{\alpha}{\theta\beta}$ is 6.4.

The aquifer probably is fairly compressible, but the computed value of α may be in error. Jacob (1940; 1941) has shown that equation (8) should include four terms in the parentheses rather than two. The two terms in the parentheses in equation 8 account for the compressibility of water and the compressibility of the aquifer skeleton. The other two terms consider the water derived from adjacent and included clay beds, and the effect of gases in the pore space of the aquifer. Water derived from adjacent and included clay beds may be important in the "sandy-unit" concept of this aquifer as previously suggested. Gas bubbles are present in the water discharged from many flowing wells, indicating that gas in the aquifer could have an effect.

To test the validity of the mean aquifer constants determined for the northern part of the area, a comparison was made between observed and computed drawdown values caused by pumping. In the spring of 1963, industrial wells 11-57-6cc and 12-56-23cc were pumped intermittently for several months and the effect was measured in wells 12-56-34da, 12-56-25cb, and 12-56-23dc. The industrial wells were pumped long enough to cause appreciable drawdowns in the observation wells but not so long that effects from the hydrologic boundaries would be noticed. Thus it was assumed that the artesian aquifer was infinite.

The drawdowns caused by intermittent pumping at different rates cannot be predicted directly from the Theis equations (1) and (2), because the equations assume that discharge is constant. The equations can be used, however, with certain modifications (Stallman, 1962). An intermittent pumping schedule at different discharge rates is shown schematically in Figure 11. If it is desired to compute the drawdown at time t_6 in an observation well at a distance r, the solution is obtained by

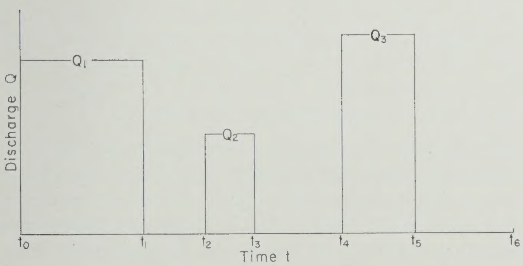

Figure 11.—Schematic diagram of intermittent discharge at different rates.

superimposing the effects of each change in discharge. Then

$$u_{0-6} = \frac{1.87\ r^2S}{Tt}$$

$$\text{Let } k = \frac{1.87\ r^2S}{T} \qquad \text{so that}$$

$$u_{0-6} = \frac{k}{t_6 - t_0}$$

$$u_{1-6} = \frac{k}{t_6 - t_1}$$

$$u_{2-6} = \frac{k}{t_6 - t_2}$$

$$u_{3-6} = \frac{k}{t_6 - t_3}$$

$$u_{4-6} = \frac{k}{t_6 - t_4}$$

$$u_{5-6} = \frac{k}{t_6 - t_5}$$

Values of W(u) are determined for the values of u from a table (Wenzel, 1942). A value is obtained for $\Sigma QW(u)$ by adding the individual QW(u) terms and considering all pumping periods as (+) and all recovery periods as (—).

$$\begin{array}{l} + Q_1W(u)_{0-6} \\ - Q_1W(u)_{1-6} \\ + Q_2W(u)_{2-6} \\ - Q_2W(u)_{3-6} \\ + Q_3W(u)_{4-6} \\ - Q_3W(u)_{5-6} \\ \hline \Sigma\ QW(u) \end{array}$$

$$\text{Then} \quad s = \frac{114.6\ \Sigma\ QW(u)}{T} \qquad (9)$$

The same type of solution may be applied to continuous discharge with step changes in the rate of discharge.

Where the drawdown in an observation well is caused by the pumping of more than one well, the

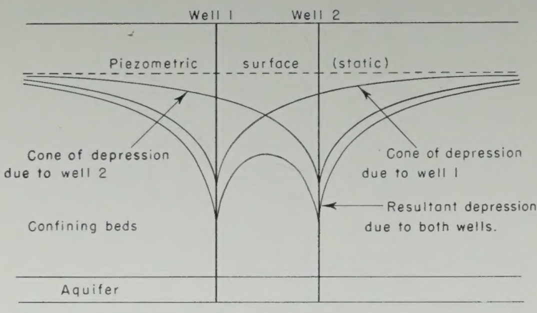

Figure 12.—Schematic diagram showing effect of well interference between two wells of equal discharge.

total drawdown is the algebraic sum of the drawdowns caused by each pumping well. Figure 12 shows the configuration of the cone of depression that results from interference between two wells of equal discharge.

The theoretical drawdown due to intermittent pumping and well interference is compared with the measured drawdown in Figure 13. Average rates of industrial withdrawal, determined from the total monthly pumpage and the number of days that the pumps were operative, were used to compute theoretical drawdown. The measured drawdowns in three different wells were affected by many diverse pressure-head changes due to pumping two wells at various rates and for various

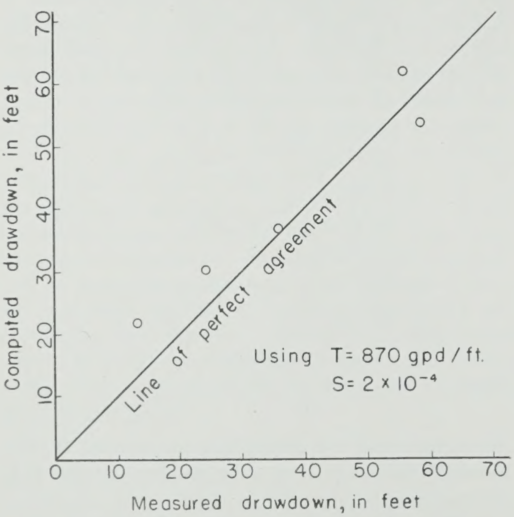

Figure 13.—Comparison of computed and measured drawdowns.

durations. Therefore, the agreement shown in Figure 13 is judged to be excellent, and the mean T and S values determined for this area are thought to be valid.

No aquifer tests were made in the outcrop area. It is assumed that the coefficient of transmissibility will be the same under water-table and artesian conditions in the aquifer. In the outcrop, however, where the water is unconfined, a comparison of the sandstones in the Fox Hills and basal part of the Hell Creek with similar sandstones in other areas of known water-table storage coefficients suggests that the storage coefficient is about 0.1, and this value will be used in subsequent computations.

LEAKAGE FROM UPPER PART OF HELL CREEK FORMATION AND FROM FORT UNION FORMATION

The beds that confine artesian aquifers are only relatively impermeable, and leakage can occur through them into the aquifer when the pressure is reduced by pumping the aquifer. Most analyses of the problem assume that (1) the leakage is proportional to the drawdown in the aquifer, (2) both the aquifer and the leaky adjacent bed are homogeneous and isotropic, and (3) the head in the upstream aquifer adjoining the leaky bed is constant. Although the permeability of the confining beds may be low, the total leakage reaching the aquifer being pumped could be very large. Leakage would tend to stabilize the cone of depression and stop its growth.

Leakage could occur into the aquifer in the Fox Hills and basal part of the Hell Creek from the upper part of the Hell Creek and from the Fort Union, but it is not likely that leakage could occur from the Pierre Shale below. The aquifer tests made on the Fox Hills and basal part of the Hell Creek failed to give any conclusive evidence that leakage did occur, but leakage might become significant if the aquifer were pumped for a long time. If leakage occurs, it will be difficult to describe algebraically because the upper confining beds are not homogeneous or isotropic.

Although the head in the aquifer in the Fox Hills and basal part of the Hell Creek has been lowered, no effects were noted in several shallow wells near industrial wells. Hydrographs of two of the shallow wells are shown in Figure 14. The slight decline of water level in well 12-56-26db began before the closest industrial well 12-56-23cc

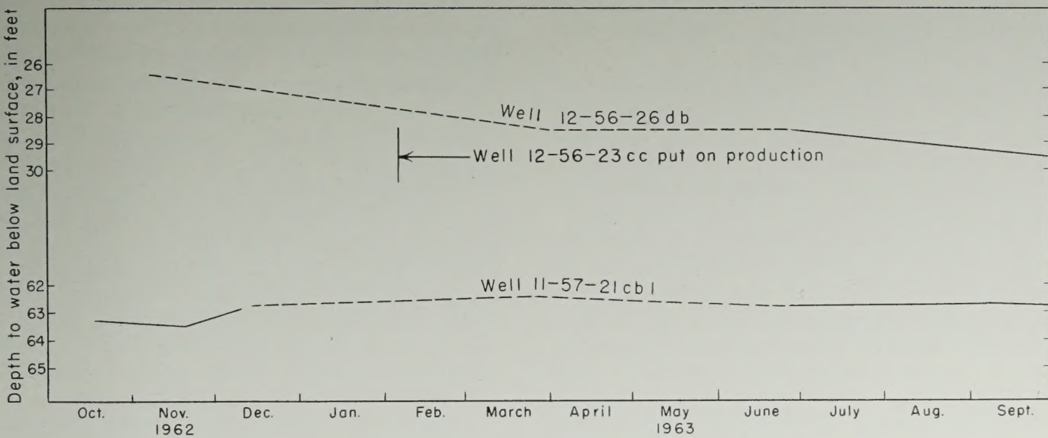

Figure 14.—Hydrographs of water levels in wells 11-57-21cb1 and 12-56-26db.

was pumped heavily, and is probably due to some other factor. None of the shallow wells in the area is deeper than about 250 feet, so not much effect would be expected. Had these wells been completed in the upper part of the Hell Creek Formation, heads might have declined. About one-half of the wells completed in the upper part of the Hell Creek or in the Fort Union have static heads that nearly coincide with the piezometric surface of the aquifer in the Fox Hills and basal part of the Hell Creek in the same area. This conformity of heads may indicate hydraulic connection between deep and shallow aquifers in certain areas, but the relation could also be fortuitous. The nonlinear recovery curves of the flow-recovery aquifer tests and the apparent high vertical compressibility of the solid skeleton of the aquifer in the Fox Hills and basal part of the Hell Creek may indicate hydraulic connection between deep and shallow aquifers. Neither hydraulic nor geologic evidence gives positive proof of leakage; hence it will be assumed that the aquifer in the Fox Hills and basal part of the Hell Creek is completely confined and that no significant leakage will be induced by pumping.

HYDROLOGIC MODEL

For this analysis the artesian aquifer can be considered to extend infinitely in all directions except near the crest of the anticline, where the aquifer is unconfined and is bounded on the eastern side by an impermeable barrier, the Pierre Shale. The contacts between the artesian and unconfined zones and the impermeable barrier are very nearly parallel and effectively of infinite length. The Theis equations (1) and (2) can be used for forecasting drawdowns in such a situation if they are applied to account adequately for the hydrologic boundaries.

If a well is pumped in an aquifer that is confined to half an infinite plane by a single impermeable barrier, each pumped well is matched with an image well (Ferris and others, 1962). The image well is placed the same distance as the real well from the impermeable barrier but on the opposite side. Both the pumped and image wells are situated on a common line perpendicular to the impermeable barrier. The pumping rate of the image well is identical to that of the real well, and the resultant changes of head in the aquifer are the sum of the effects from the real well and the image well. The resultant hydraulic gradient is zero along the boundary, and theoretically no flow can occur across the boundary. This system is shown in Figure 15.

Another type of boundary is that encountered when a well in an unconfined aquifer is pumped, and the aquifer is crossed by a single stream, a line source, that is in hydraulic connection with the water table. It is assumed that the stream is linear and of infinite length. If the stage of the stream does not change, the resultant changes of head in the aquifer are the sum of the effects from the real well and an image well located with respect to the boundary as in the example above. The image well injects water at a rate identical to the pumping rate of the real well. There is no drawdown at the stream, and the steepened hydraulic

gradient at the stream indicates movement of water from the stream to the water table. This system is shown in Figure 16.

The boundary system on the western flank of the Cedar Creek anticline is comparable to a combination of the two boundary systems discussed above. There is an area over which the aquifer is unconfined, adjoining an impermeable barrier across which no flow can occur, and the unconfined zone has certain similarities to a stream because its storage coefficient is estimated to be 500 times larger than that of the artesian aquifer. The outcrop would not be hydraulically similar to a stream of constant stage, however, unless the recharge increases in the outcrop so as to equal the withdrawals in the outcrop due to pumping at the proposed rates and durations. Flow to wells in the vicinity of the boundary between artesian and water-table conditions has been treated in the literature (Bixel and others, 1963).

According to the hydrologic data, the ratio of coefficients of storage for the unconfined and confined zones of the aquifer is about 500/1. Response to pumping in composite flow regions with such a large ratio of S values, and a uniform transmissibility, are comparable with the response to pumping in the vicinity of a stream. The appropriate image-well system has already been defined in Figure 16. Use of such a flow model for the western flank of the Cedar Creek anticline is justified in view of the theoretical response curves presented by Bixel and others (1963, Fig. 10) if one can justifiably ignore the hydraulic effects of the impermeable barrier. For the period of pumping being considered in this report, computed drawdowns based on the flow situation of Figure 16 will be adequate for engineering purposes. Presently there is no known equation that computes the extent to which the impermeable barrier affects drawdown, but such a hydrologic situation could be treated by electric analog.

The drawdown curve of aquifer test 9 concurs with the previous analysis. The observation well used in this drawdown test lies just west of the contact between artesian and water-table conditions. During about 5½ days of pumping, a small

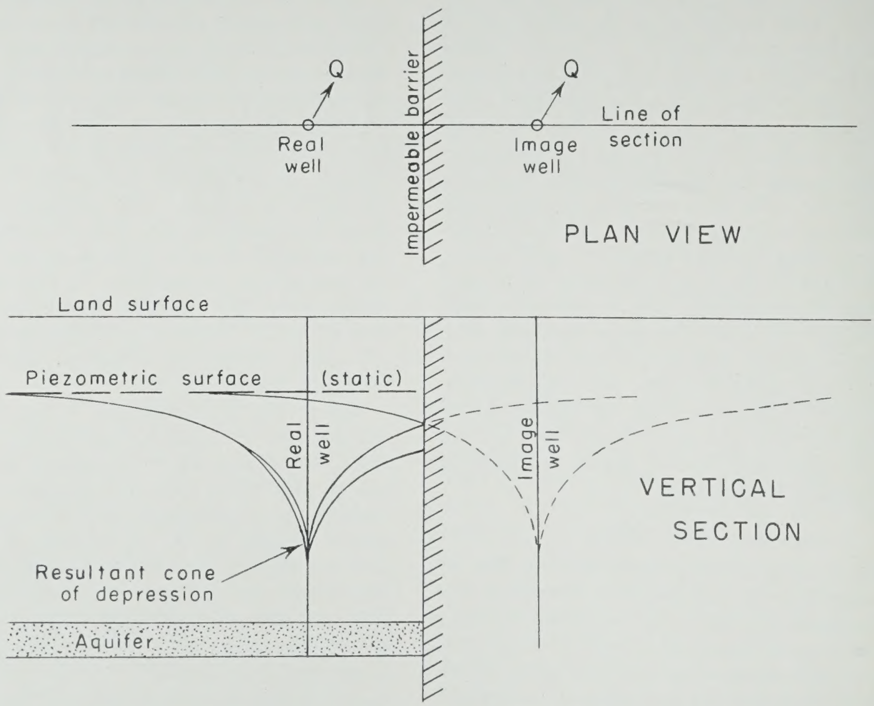

Figure 15.—Schematic diagram showing effect of pumping a well near an impermeable barrier.

drawdown occurred in the artesian aquifer at the observation well. Near the end of the test, the slow-acting drainage from the outcrop stabilized the cone of depression and essentially stopped its growth at that point.

SUMMARY OF ASSUMPTIONS

The following is a summary of the assumptions that were made in order to determine the effect of industrial withdrawals of ground water from the aquifer in the Fox Hills Sandstone and basal part of the Hell Creek Formation.

(1) Ground water will be withdrawn from the wells at the rates shown in Figure 8.

(2) The aquifer constants of the artesian region that will be affected are T = 870 gpd/ft, and $S = 2 \times 10^{-4}$.

(3) There will be no leakage to or from the aquifer in the Fox Hills and basal part of the Hell Creek after pumping begins.

(4) Recharge in the outcrop will be sufficient to maintain the water table at its present position. Therefore, the impermeable barrier will have no effect on drawdown in the aquifer.

(5) There will be no other recharge to, or discharge from the aquifer.

(6) A line source will be assumed to lie along the centerline of the outcrop of the aquifer, and each real well will have, at the image position, a hyopthetical injection well that injects at a rate equal to the rate of pumping by the real well.

(7) All real and image wells will affect the artesian region.

(8) The Theis equations are applicable, subject to the above restrictions.

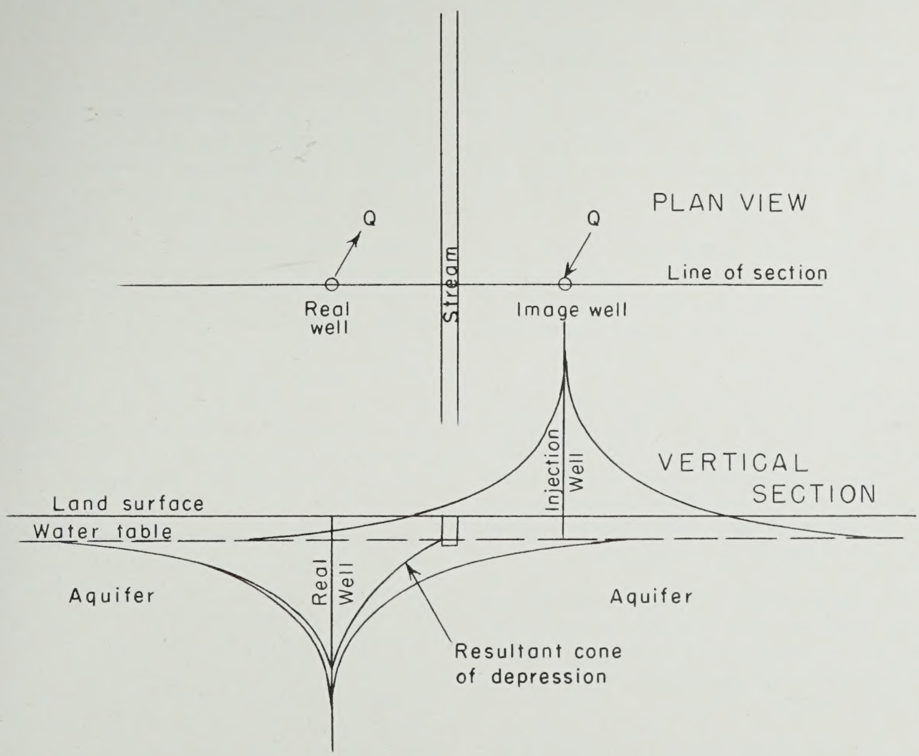

Figure 16.—Schematic diagram showing effect of pumping a well near a stream of constant stage.

SOLUTION

The drawdown or depression of the piezometric surface of the aquifer was plotted on Plates 3, 4, and 5 by the use of special drawdown scales. Conover and Reeder (1963) describe the construction of drawdown scales that show the variation of drawdown with distance from a pumped well. If the drawdown scale is chosen to conform with the map scale, then the drawdown scale may be pivoted about the well location on the map and the drawdown at distance from the well may be noted. One scale may be constructed for each set of constant values of T, S, Q, and t.

For the solution an adjustment was made for the steplike decline in discharge for three of the wells as shown in Figure 8. Stallman (1962) has shown that the effects of steplike decline in discharge can be accounted for by adding recharge wells at the real well. The wells recharge at a rate equal to the change and the effect begins when the change occurs. For example, the proposed discharge rates for well 12-56-23cc for 1964-68 are:

Year	Discharge, gpm	Change in discharge, gpm
1964	248	
		-9
1965	239	
		-8
1966	231	
		-10
1967	221	
		-8
1968	213	

The effect at the end of 1968 at any point in an infinite aquifer will be caused by a well pumping 248 gpm for 5 years minus the effects of injections at 9, 8, 10, and 8 gpm for 4-, 3-, 2-, and 1-year periods respectively.

An adjustment was also made on the drawdown scales for well 11-57-17bc. This well began discharging at a constant rate in 1959. Thus, the effect of 5 years of discharge was already noted in 1964, and all future drawdown predictions are based on the effect of the entire pumping period minus the effect during the first 5 years.

The drawdown scales fail to account for the hydrologic boundary, but they can be used with the image wells to give the desired result. When the scales are used with the image wells, they become recovery scales.

The computed depression of the piezometric surface by the end of 1968, 1973, and 1984 was plotted on Plates 3, 4, and 5. The control points on these plates are the net result of the sum of the drawdowns from the four real wells minus the sum of the recoveries from the four image wells. The computations were greatly facilitated by a high-speed computer solution of the variation of drawdown with distance. The computer solution was provided by the Computations Branch of the U. S. Geological Survey in Denver, Colorado.

The control points were contoured to show the configuration of the depressed piezometric surface and to permit an estimate of the resulting depression at any point by interpolation between contours. Contours were not drawn in the vicinity of the pumped wells for the years 1968 or 1973, because there are very few wells to be affected in this area and because the shape of the merged cones of depression would be complicated. The contours extend slightly into the southern part of the area, where the coefficients of transmissibility and storage are higher than in the northern part. Therefore, the small drawdowns predicted for this area are probably overestimated.

The head at any well at the end of 1968, 1973, or 1984 can be determined from Plates 3, 4, and 5. On these plates the head above or below land surface in 1962-63 is shown for comparison with the depression contours. The new head is the algebraic sum of the head in 1962-63 and the depression interpolated from the contours. For example, if a flowing artesian well had 10.7 feet of head above land surface in 1962-63, and the depression after a certain period of pumping is 12.7 feet, the well will cease to flow and the head will be 2.0 feet below land surface. If a nonflowing artesian well had a head 16.4 feet below land surface in 1962-63, and the depression after a certain period of pumping is 3.3 feet, the new head will be 19.7 feet below land surface.

Significant drawdowns can be expected to the west of the industrial wells at the end of 1968. The drawdowns increase slightly by the end of 1973 as the cones spread westward. During the first 10 years of pumping, the effects on some of the nearby private wells will be noticeable, but the municipal wells are so distant that the effects on them are small. By the end of 1984 the recovery of head has been so large that there is only a slight residual effect.

RELATED FACTORS THAT AFFECT CONTROL AND USE OF HYDROLOGIC SYSTEM

The importance of the aquifer in the Fox Hills Sandstone and basal part of the Hell Creek Formation has been emphasized because it is the only dependable aquifer in the area of investigation that can be developed economically. Therefore, any unnecessary pumping or flowing from wells is a waste of both artesian head and ground water.

The effects of flowing domestic wells can be detected in the area. Well number 9-55-17db is presently flowing about 40 gpm and has been flowing since 1935. On Plate 2, the displacement of the piezometric contours near this well shows the decline in artesian head. There also has been accompanying loss of at least 600 million gallons of water from the aquifer.

An old abandoned flowing well in Mildred, Montana, is believed to penetrate the aquifer in the Fox Hills and basal part of the Hell Creek. When the well is shut off, it is reported that wells as distant as one mile begin to recover artesian head. When freezing weather ruptures the pipe on the well, flow begins and the nearby wells lose artesian head.

Although slight use of a domestic well at a constant or intermittent rate will not produce a noticeable effect at a distance of several miles, there will be a noticeable loss of artesian head at the well, owing to its own flow. The rate of head loss is greatest at first, so the static artesian head in a new well will decline rapidly as the well is used. For steady pumping or flow of 4 gpm, the drawdown at a distance of 1 foot from the well as it varies with time is shown in Figure 17. Two curves are shown, one to give the effect in the northern part (T = 870 gpd/ft) and one the southern part (T = 2,600 gpd/ft). It is impossible to ever recover all of the static head unless the aquifer is recharged nearby. Therefore, a newly drilled well that barely flows will probably cease flowing after the well is used and its cone of depression begins to grow. It may be necessary to allow a well to flow constantly at a low rate in order to furnish water for livestock or to prevent pipe rupture during freezing weather. The discharge should be kept at a minimum, however, to conserve artesian head.

To emphasize further the rate of loss of artesian head, consider the hypothetical dewatering of the aquifer in the Fox Hills Sandstone and basal part of the Hell Creek Formation in the northern part of the area. Assume the average aquifer thickness is 100 feet; the average aquiclude thickness is 900 feet; and the average artesian head is at land surface. The removal of only 1/56 of the water from the aquifer will lower the head 900 feet to the top of the aquifer. The removal of the

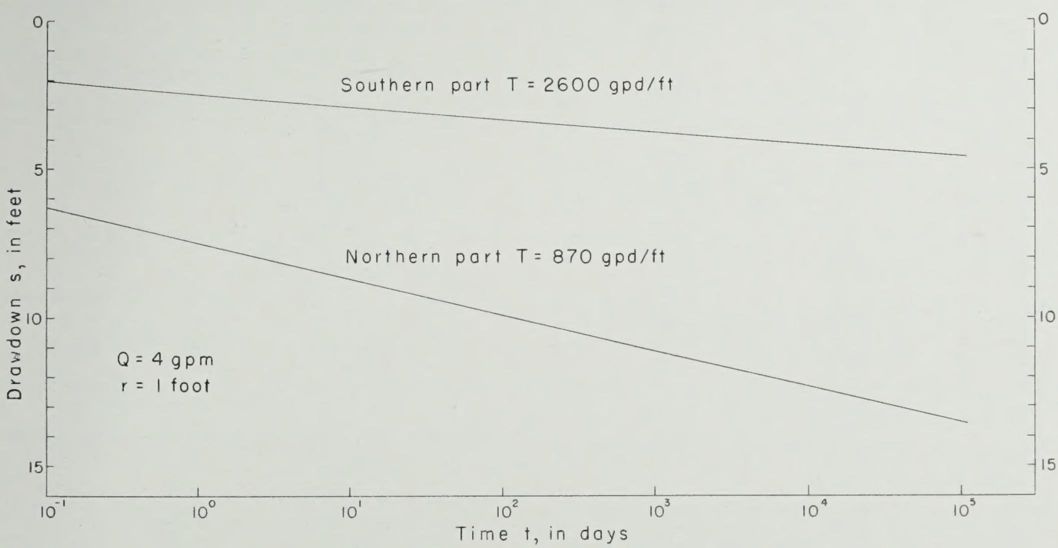

Figure 17.—Variation of drawdown with time at a distance of 1 foot from a pumped or flowing well of constant discharge.

remaining 55/56 of the water will lower the water table an additional 100 feet for complete aquifer dewatering.

RECOMMENDATIONS PERTAINING TO HYDROLOGIC SYSTEM

Any new well drilled to the aquifer in the Fox Hills Sandstone and basal part of the Hell Creek Formation should completely penetrate the aquifer to minimize well losses. The well should be completely cased and the casing firmly attached to the drill hole by cementing or some other method. Casing large enough to accommodate a pump should be installed well below the land surface. The section of casing could be repaired if necessary and would allow adequate pump submergence for some time even if artesian pressure does decline. In the lower part of the well, smaller casing could be used if it is sealed to the larger casing above. Well screens may be desirable in municipal, industrial, and shallow domestic wells to insure sand-free water.

The complexity of the theory presented for the analysis of the effect of industrial use of ground water on the hydrologic system is apparent. It is recommended that a program be initiated for the periodic measurement of heads for the verification of the basic assumptions that were made in the analysis. Any changes in withdrawal patterns will affect the conclusions in this report, but adjustments in computations could be made in order to take account of these changes.

All domestic, municipal, and industrial users of ground water should strive to conserve water and artesian pressure in the aquifer in the Fox Hills and basal part of the Hell Creek and other aquifers in order to safeguard this vital resource.

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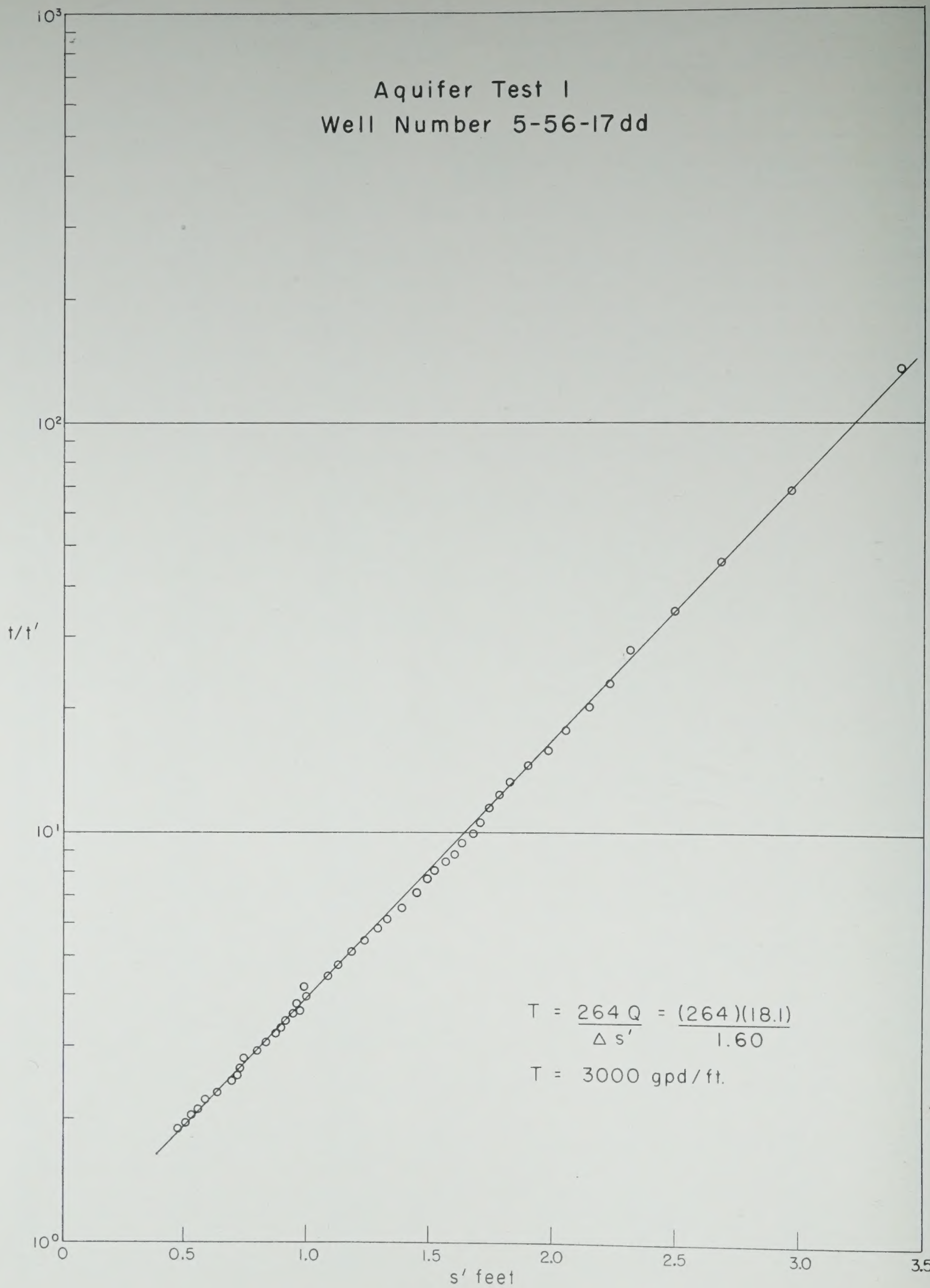
Aquifer test 1 (Flow recovery test)
Well number 5-56-17dd
July 16, 1963

Test conducted by O. James Taylor
Static head 47.25 feet of water
Average discharge, Q = 18.1 gpm

Time t (minutes)	Time t′ (minutes)	Head (feet of water)	Reservoir depression (feet of water)	Adjusted head h′ (feet of water)	t/t′	Residual drawdown s′ (feet of water)
136	1	43.39	0.45	43.84	136	3.41
137	2	43.83		44.28	68.5	2.97
138	3	44.11		44.56	46.0	2.69
139	4	44.31		44.76	34.8	2.49
140	5	44.48		44.93	28.0	2.32
141	6	44.57		45.02	23.5	2.23
142	7	44.65		45.10	20.3	2.15
143	8	44.74		45.19	17.9	2.06
144	9	44.82		45.27	16.0	1.98
145	10	44.90		45.35	14.5	1.90
146	11	44.97		45.42	13.2	1.83
147	12	45.02	.45	45.47	12.2	1.78
148	13	45.05		45.50	11.4	1.75
149	14	45.09		45.54	10.6	1.71
150	15	45.12		45.57	10.0	1.68
151	16	45.17		45.62	9.45	1.63
152	17	45.20		45.65	8.95	1.60
153	18	45.23		45.68	8.52	1.57
154	19	45.28		45.73	8.10	1.52
155	20	45.30	.45	45.75	7.75	1.50
157	22	45.35		45.80	7.13	1.45
159	24	45.42		45.87	6.62	1.38
161	26	45.47		45.92	6.20	1.33
163	28	45.51		45.96	5.82	1.29
165	30	45.56		46.01	5.50	1.24
168	33	45.62		46.07	5.10	1.18
171	36	45.67		46.12	4.75	1.13
174	39	45.71	.45	46.16	4.47	1.09
177	42	45.80		46.25	4.22	1.00
180	45	45.80		46.25	4.00	1.00
183	48	45.83		46.28	3.82	.97
186	51	45.82		46.27	3.65	.98
187	52	45.85		46.30	3.60	.95
189	54	45.88		46.33	3.50	.92
192	57	45.90		46.35	3.38	.90
195	60	45.92		46.37	3.25	.88
200	65	45.97		46.42	3.08	.83
205	70	46.00		46.45	2.93	.80
210	75	46.05		46.50	2.80	.75
216	81	46.07	.45	46.52	2.67	.73
220	85	46.08		46.53	2.59	.72
225	90	46.10		46.55	2.50	.70
235	100	46.16		46.61	2.35	.64
245	110	46.21		46.66	2.22	.59
255	120	46.24		46.69	2.12	.56
265	130	46.27		46.72	2.04	.53
275	140	46.29		46.74	1.96	.51
285	150	46.32		46.77	1.90	.48

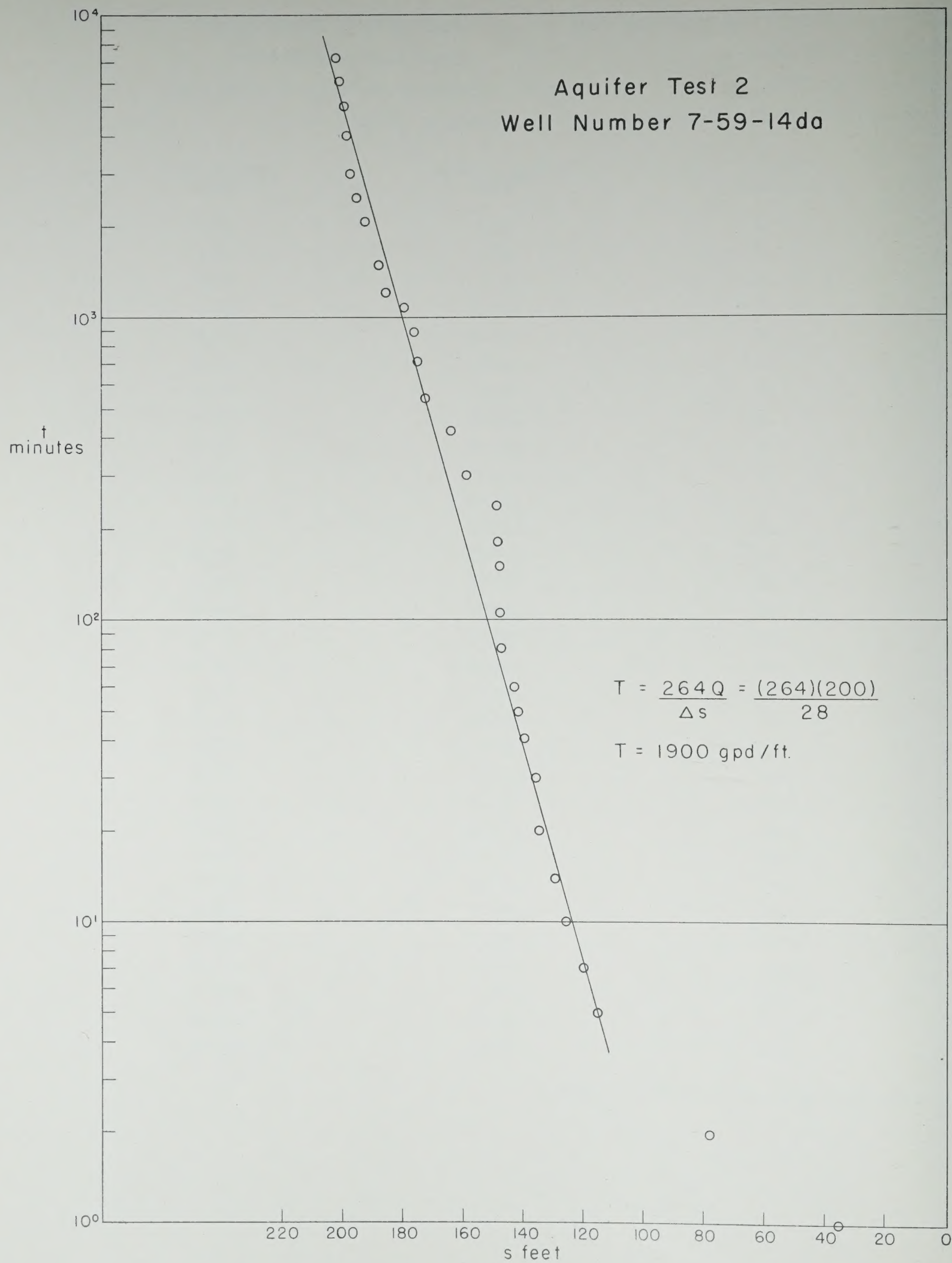

Aquifer Test I
Well Number 5-56-17dd
10^3
10^2
10^1
10^0
t/t'
$T = \frac{264\,Q}{\Delta s'} = \frac{(264)(18.1)}{1.60}$
T = 3000 gpd/ft.
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
s' feet

Aquifer test 2 (Single well drawdown test)
Well number 7-59-14da
December 17-22, 1962
Test conducted by Frederickson's Inc.

Analysis by O. James Taylor
Static water level 90.0 feet
Average discharge, Q = 200 gpm

Time t (minutes)	Depth to water (feet)	Drawdown s (feet)
1	124.5	34.5
2	167.1	77.1
5	205.8	115.8
7	210.40	120.4
10	215.55	125.55
14	219.3	129.3
20	225.3	135.3
30	226.35	136.35
40	229.50	139.50
50	232.30	142.30
60	233.40	143.4
80	237.00	147.0
105	238.65	148.20
150	238.62	148.62
180	238.58	148.58
240	238.63	148.63
300	249.38	159.38
420	254.23	164.23
540	263.28	173.28
720	265.4	175.4
900	267.26	177.26
1,080	269.50	179.50
1,200	275.65	185.65
1,500	278.00	188.0
2,040	283.22	193.22
2,520	285.20	195.20
3,000	287.11	197.11
3,960	287.55	197.55
4,980	289.17	199.17
6,000	290.75	200.75
7,200	292.05	202.05

Note: Data given are those selected for plotting.


Aquifer Test 2
Well Number 7-59-14da
$T = \frac{264Q}{\Delta s} = \frac{(264)(200)}{28}$
T = 1900 gpd/ft.
t minutes
s feet
10^4
10^3
10^2
10^1
10^0
220
200
180
160
140
120
100
80
60
40
20
0

Log of well 7-59-14da

Well owner, City of Baker

Log provided by City of Baker

Depth (feet) From	To	Thickness (feet)	
0	64	64	Shale, gray
64	67	3	Shale, green, hard
67	117	50	Shale, gray
117	130	13	Sand, dirty
130	168	38	Shale, blue
168	171	3	Hard, brown (?)
171	187	16	Sand, gray
187	219	32	Shale, brown and green
219	239	20	Sand
239	265	26	Shale, gray and green
265	297	32	Shale, brown and gray
297	303	6	Sand
303	306	3	Shale, blue
306	314	8	Sand
314	338	24	Shale and sand, gray
338	403	65	Sand
403	463	60	Shale and sand, gray
463	465	2	Shale, gray, hard
465	491	26	Sand
491	550	59	Shale, gray, soft
550	632	82	Shale, gray and blue, hard
632	643	11	Sand
643	667	24	Shale, hard
667	687	20	Shale, soft
687	689	2	Limestone, hard
689	701	12	Shale
701	800	99	Shale

Assumed aquifer thickness 121 feet.

Screen and filter sand installed from 340 feet to 500 feet.

Aquifer test 3 (Drawdown test) March 26-27, 1962

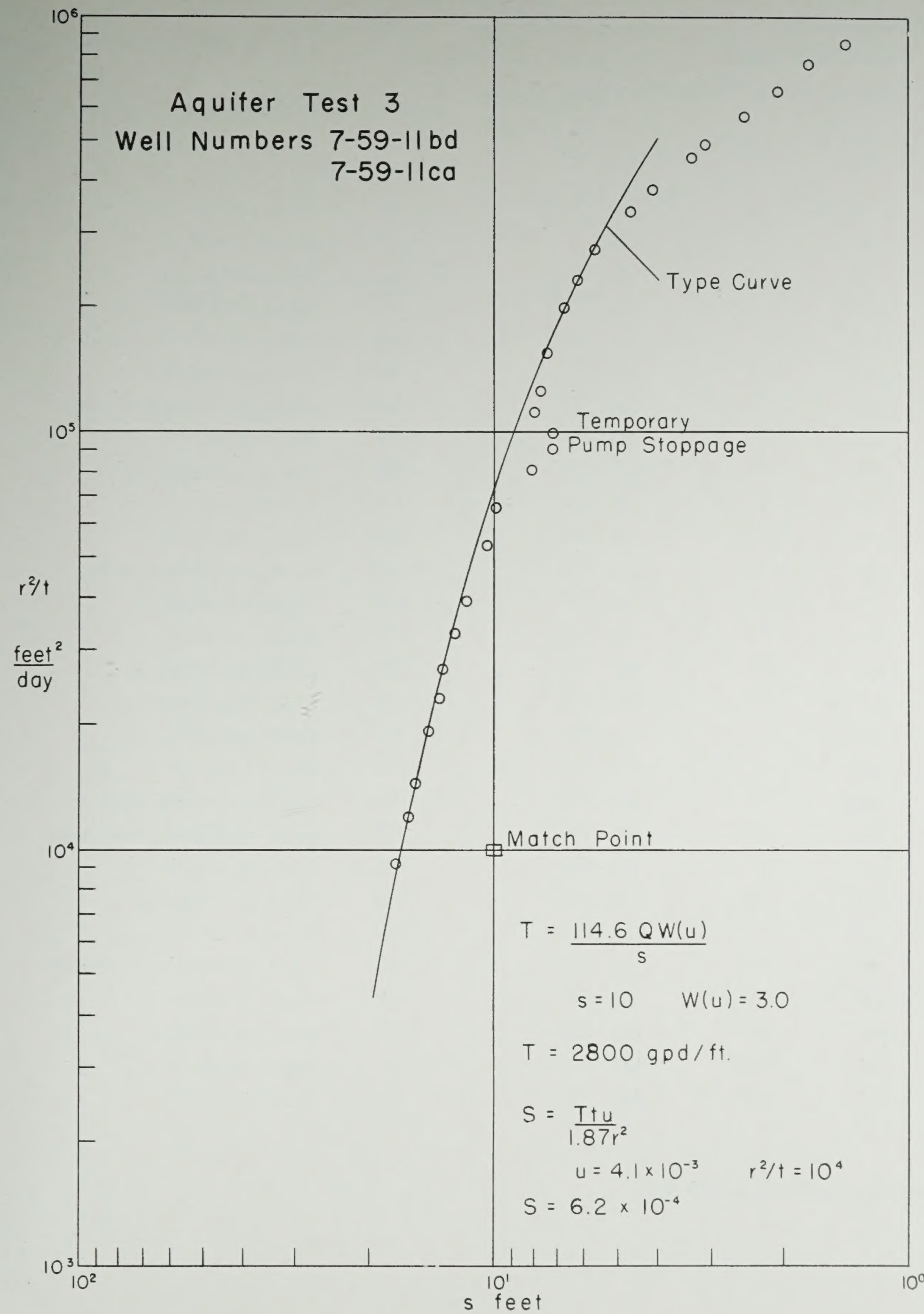
Well number 7-59-11bd (Pumped well) Test conducted by Ross K. Petersen

Well number 7-59-11ca (Observation well) Analysis by O. James Taylor

Average discharge, Q = 81 gpm, r = 98 feet, static water level 59.75 feet

Time t (minutes)	r^2/t (ft^2/day)	Depth to water (feet)	Drawdown s (feet)
14	9.90×10^5	60.78	1.03
16	8.65×10^5	61.16	1.41
18	7.70×10^5	61.50	1.75
21	6.60×10^5	61.83	2.08
24	5.77×10^5	62.25	2.50
28	4.94×10^5	62.87	3.12
30	4.62×10^5	63.12	3.37
36	3.85×10^5	63.92	4.17
40	3.46×10^5	64.47	4.72
50	2.77×10^5	65.42	5.67
60	2.31×10^5	66.08	6.33
70	1.98×10^5	66.50	6.75
90	1.54×10^5	67.25	7.50
110	1.26×10^5	67.50	7.75
124	1.12×10^5	67.70	7.95
140	9.90×10^4	67.00	7.25
151	9.19×10^4	67.00	7.25
170	8.13×10^4	67.92	8.17
210	6.60×10^4	69.68	9.93
255	5.42×10^4	70.42	10.67
350	3.95×10^4	71.42	11.67
420	3.30×10^4	72.13	12.38
513	2.70×10^4	73.00	13.25
605	2.29×10^4	73.33	13.58
720	1.92×10^4	74.16	14.41
970	1.43×10^4	75.30	15.55
1,155	1.20×10^4	75.82	16.07
1,501	9.20×10^3	76.90	17.15

Note: Data given are those selected for plotting.


Aquifer Test 3
Well Numbers 7-59-11bd
7-59-11ca
Type Curve
Temporary
Pump Stoppage
Match Point
$T = \frac{114.6\ QW(u)}{s}$
$s = 10 \qquad W(u) = 3.0$
$T = 2800$ gpd/ft.
$S = \frac{Ttu}{1.87r^2}$
$u = 4.1 \times 10^{-3} \qquad r^2/t = 10^4$
$S = 6.2 \times 10^{-4}$
r^2/t
$\frac{feet^2}{day}$
10^6
10^5
10^4
10^3
10^2
10^1
10^0
s feet

Log of well 7-59-11ca

Well owner, City of Baker

Log provided by George Askin, Miles City, Montana

Depth (feet)			
From	To	Thickness (feet)	
0	80	80	Clay, yellow
80	90	10	Gumbo, black
90	130	40	Shale, dark
130	133	3	Sand, some water
133	145	12	Shale, sandy
145	230	85	Shale, variegated
230	240	10	Sandstone, blue, with water
240	248	8	Shale, blue
248	270	22	Shale, variegated
270	277	7	Limestone
277	294	17	Shale, blue
294	304	10	Sand, blue, with water
304	330	26	Shale, dark blue
330	336	6	Shale, sandy
336	400	64	Shale, very hard
400	420	20	Shale, blue
420	434	14	Sand, with water
434	437	3	Shale, blue
437	452	15	Shale, gray, very hard
452	487	35	Sand, with abundant water
487	510	23	Shale, brown
510	515	5	Sand, with water
515	537	22	Shale, blue
537	576	39	Sand, with abundant water
576	580	4	Shale, blue
580	618	38	Sand with water
618	628	10	Shale, sandy
628	685	57	Pierre Shale

Assumed aquifer thickness 159 feet.

Aquifer test 4 (Flow test)

Well number 8-56-27bc

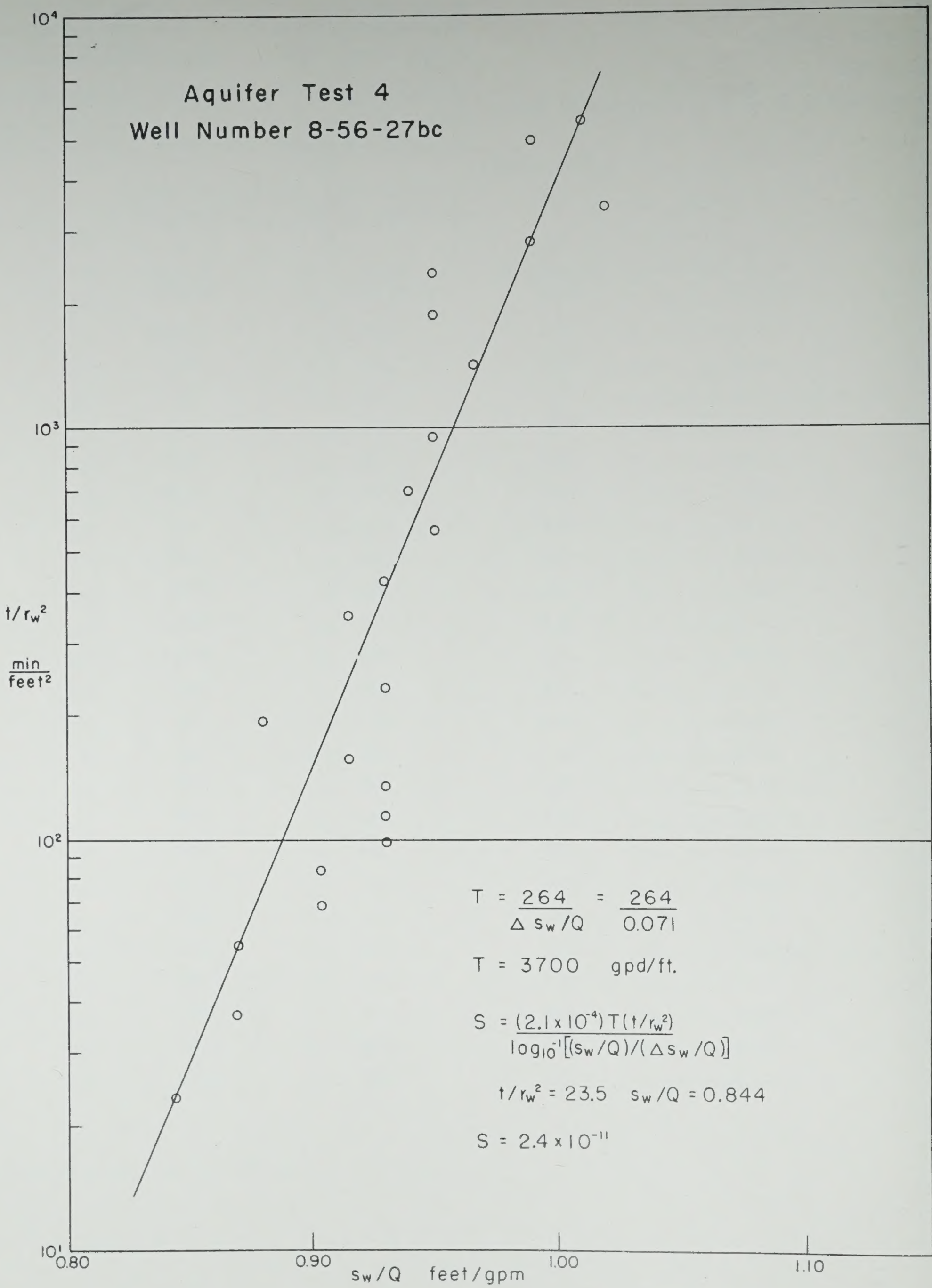
August 9, 1963

Test conducted by R. G. McMurtrey and O. James Taylor

Static head	28.21 feet of water
Reservoir depression	+ 0.40 feet of water
Actual static head	28.61 feet of water
Flowing head	1.88 feet of water
Reservoir depression	+ 0.30 feet of water
Actual flowing head	2.18 feet of water

$s_w = 28.61 - 2.18 = 26.43$ feet of water.
$r_w = 1.46 \times 10^{-1}$ ft. $(r_w)^2 = 2.13 \times 10^{-2}$ ft^2

Time t (min-sec)	**Discharge Q (gpm)**	**s_w/Q (feet/gpm)**	**$t/(r_w)^2$ (min/ft^2)**
00-11	30.4	0.869	8.62
00-30	31.3	.844	23.5
00-48	30.4	.869	37.7
01-10	30.4	.869	54.9
01-28	29.2	.903	69.0
01-47	29.2	.903	83.8
02-05	28.4	.930	98.0
02-25	28.4	.930	113.5
02-50	28.4	.930	133.0
03-20	28.8	.915	156.5
04-06	30.0	.880	192.5
04-57	28.4	.930	232
07-30	28.8	.915	352
08-56	28.4	.930	420
12-01	27.8	.950	562
14-58	28-1	.940	705
20-00	27.8	.950	940
30-00	27.4	.967	1,410
40-00	27.8	.950	1,880
50-00	27.8	.950	2,350
60-00	26.7	.990	2,820
70-00	25.8	1.020	3,290
105-00	26.7	.990	4,935
117-20	26.1	1.010	5,500


Aquifer Test 4
Well Number 8-56-27bc
10^4
10^3
10^2
10^1
t/r_w^2
$\frac{min}{feet^2}$
$T = \frac{264}{\Delta s_w/Q} = \frac{264}{0.071}$
T = 3700 gpd/ft.
$S = \frac{(2.1 \times 10^{-4})\,T\,(t/r_w^2)}{\log_{10}^{-1}[(s_w/Q)/(\Delta s_w/Q)]}$
$t/r_w^2 = 23.5 \quad s_w/Q = 0.844$
$S = 2.4 \times 10^{-11}$
0.80
0.90
1.00
1.10
s_w/Q feet/gpm

Aquifer test 5 (Flow recovery test)

Well number 8-56-27bc

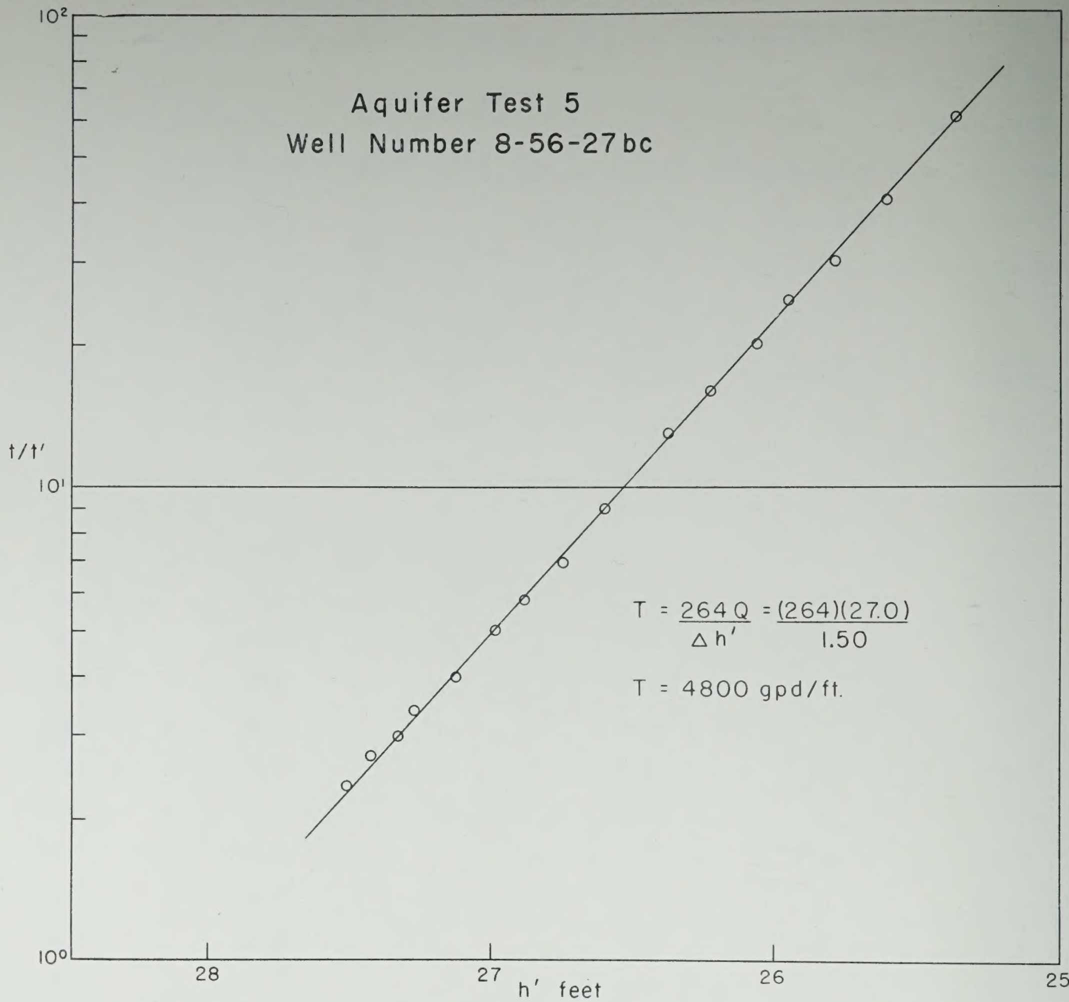
August 9, 1963

Test conducted by R. G. McMurtrey and O. James Taylor

Static head 28.61 feet of water

Average discharge, Q = 27.0 gpm

Time t (minutes)	Time t′ (minutes)	Head (feet of water)	Reservoir depression (feet of water)	Adjusted head h′ (feet of water)	t/t′
120	0	1.88	0.30	2.18	
121	1	24.56	.38	24.94	121
122	2	24.99	.38	25.37	61.0
123	3	25.24	.38	25.62	41.0
124	4	25.42	.38	25.80	31.0
125	5	25.58	.38	25.96	25.0
126	6	25.69	.38	26.07	21.0
128	8	25.86	.38	26.24	16.0
130	10	26.00	.38	26.38	13.0
135	15	26.23	.38	26.61	9.00
140	20	26.37		26.75	7.00
145	25	26.50	.39	26.89	5.80
150	30	26.60		26.99	5.00
160	40	26.75		27.14	4.00
170	50	26.89		27.28	3.40
180	60	26.95	.39	27.34	3.00
190	70	27.04		27.43	2.71
210	90	27.13		27.52	2.33



Log of well 8-56-27bc

Well owner, Mr. Reiger

Log provided by George Askin, Miles City, Montana

Depth (feet) From	To	Thickness (feet)	
0	30	30	Gravel
30	100	70	Sand
100	400	300	Gumbo
400	430	30	Sand
430	580	150	Gumbo
580	940	360	Sand

Assumed aquifer thickness 460 feet

Flow when drilled, 30 gpm

Aquifer test 6 (Flow test)

Well number 9-55-27bb

July 10, 1963

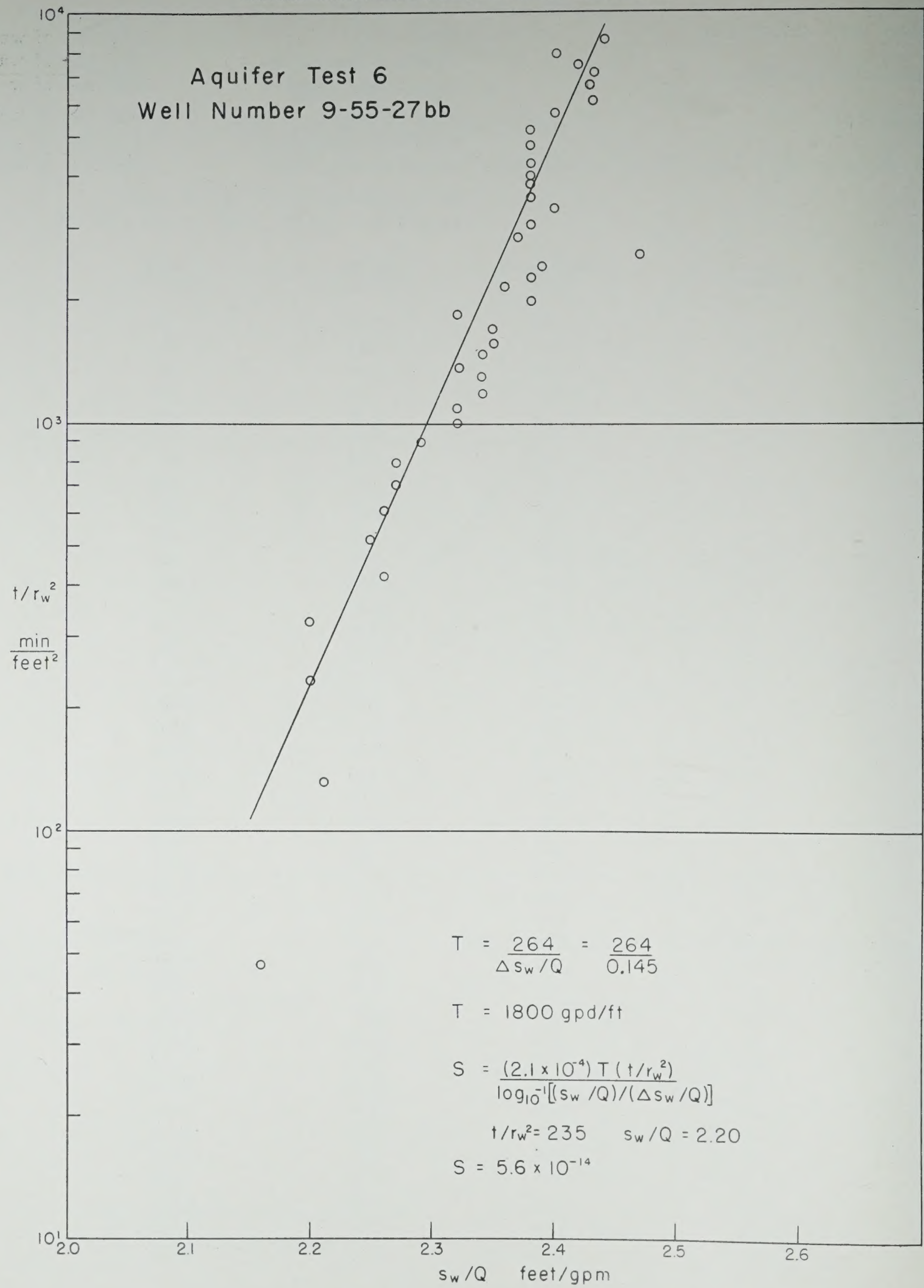
Test conducted by O. James Taylor and Bill Almy

Static head	12.55 feet of water
Reservoir depression	+ 0.30 feet of water
Actual static head	12.85 feet of water
Flowing head	4.81 feet of water
Reservoir depression	+ 0.15 feet of water
Actual flowing head	4.96 feet of water

$s_w = 12.85 - 4.96 = 7.89$ feet of water

$r_w = 1.46 \times 10^{-1}$ ft. $(r_w)^2 = 2.13 \times 10^{-2}$ ft^2

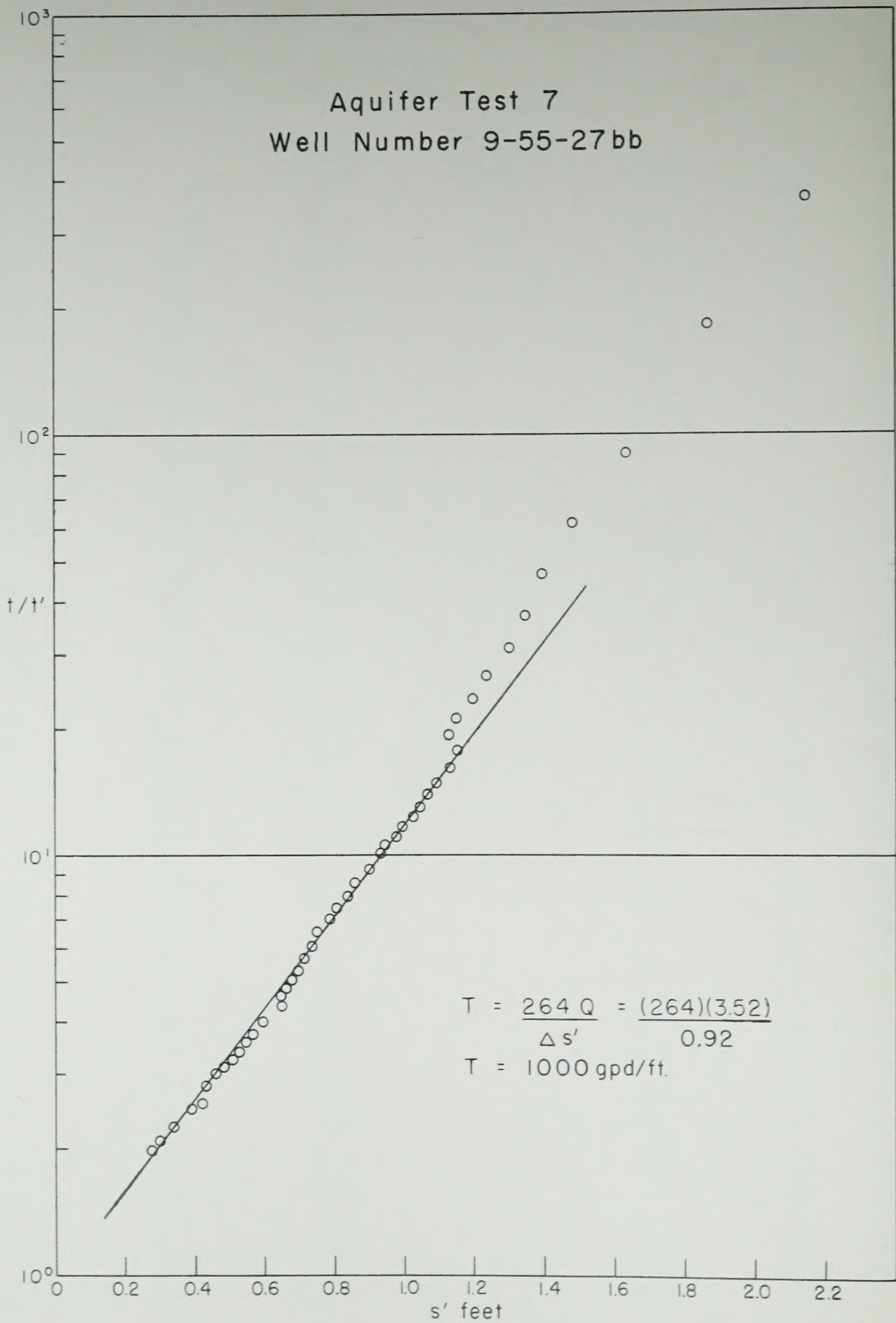
Time t (minutes)	Discharge Q (gpm)	s_w/Q (feet/gpm)	$t/(r_w)^2$ (min/ft^2)
1	3.65	2.16	47
3	3.57	2.21	131
5	3.58	2.20	235
7	3.58	2.20	329
9	3.49	2.26	423
11	3.50	2.25	517
13	3.48	2.26	611
15	3.47	2.27	705
17	3.47	2.27	799
19	3.44	2.29	893
21	3.39	2.32	986
23	3.39	2.32	1,080
25	3.38	2.34	1,174
27	3.37	2.34	1,269
29	3.39	2.32	1,360
31	3.38	2.34	1,455
33	3.36	2.35	1,550
36	3.35	2.35	1,691
39	3.39	2.32	1,832
42	3.32	2.38	1,972
45	3.34	2.36	2,120
48	3.32	2.38	2,260
51	3.30	2.39	2,400
54	3.19	2.47	2,540
60	3.33	2.37	2,820
65	3.32	2.38	3,060
70	3.29	2.40	3,290
75	3.32	2.38	3,520
81	3.31	2.38	3,800
85	3.32	2.38	4,000
90	3.32	2.38	4,230
100	3.32	2.38	4,700
110	3.32	2.38	5,170
120	3.28	2.40	5,640
130	3.25	2.43	6,110
140	3.25	2.43	6,580
150	3.25	2.43	7,050
160	3.26	2.42	7,510
170	3.28	2.40	7,990
180	3.24	2.44	8,450


Aquifer Test 6
Well Number 9-55-27bb
10^4
10^3
10^2
10^1
t/r_w^2
$\frac{\text{min}}{\text{feet}^2}$
2.0
2.1
2.2
2.3
2.4
2.5
2.6
s_w/Q feet/gpm
$T = \frac{264}{\Delta s_w/Q} = \frac{264}{0.145}$
$T = 1800$ gpd/ft
$S = \frac{(2.1 \times 10^{-4})\, T\, (t/r_w^2)}{\log_{10}^{-1}[(s_w/Q)/(\Delta s_w/Q)]}$
$t/r_w^2 = 235$ $s_w/Q = 2.20$
$S = 5.6 \times 10^{-14}$

Aquifer test 7 (Flow recovery test)
Well number 9-55-27bb
July 3, 1963

Test conducted by O. James Taylor
Static head 12.60 feet of water
Average discharge, Q = 3.52 gpm

Time t (minutes)	Time t′ (minutes)	Head (feet of water)	Reservoir depression (feet of water)	Adjusted head h′ (feet of water)	t/t′	Residual drawdown s′ (feet of water)
180.5	0.5	10.20		10.45	361	2.15
181	1	10.48	0.25	10.73	181	1.87
182	2	10.71		10.96	91.0	1.64
183	3	10.86		11.11	61.0	1.49
184	4	10.95		11.20	46.0	1.40
185	5	11.00		11.25	37.0	1.35
186	6	11.05		11.30	31.0	1.30
187	7	11.11		11.36	26.7	1.24
188	8	11.15		11.40	23.5	1.20
189	9	11.20		11.45	21.0	1.15
190	10	11.22		11.47	19.0	1.13
191	11	11.19		11.44	17.4	1.16
192	12	11.21		11.46	16.0	1.14
193	13	11.25		11.50	14.8	1.10
194	14	11.28	.25	11.53	13.9	1.07
195	15	11.30		11.55	13.0	1.05
196	16	11.32		11.57	12.2	1.03
197	17	11.35		11.60	11.6	1.00
198	18	11.37		11.62	11.0	0.98
199	19	11.40		11.65	10.5	0.95
200	20	11.42		11.67	10.0	0.93
202	22	11.45		11.70	9.18	0.90
204	24	11.49		11.74	8.47	0.86
206	26	11.51		11.76	7.93	0.84
208	28	11.54		11.79	7.45	0.81
210	30	11.56		11.81	7.00	0.79
213	33	11.60		11.85	6.46	0.75
216	36	11.61	.25	11.86	6.00	0.74
219	39	11.63		11.88	5.60	0.72
222	42	11.65		11.90	5.29	0.70
225	45	11.67		11.92	5.00	0.68
228	48	11.69		11.94	4.77	0.66
231	51	11.70		11.95	4.61	.65
234	54	11.70		11.95	4.33	.65
240	60	11.75		12.00	4.00	.60
245	65	11.78		12.03	3.77	.57
250	70	11.80		12.05	3.58	.55
255	75	11.82		12.07	3.40	.53
260	80	11.84		12.09	3.25	.51
265	85	11.87		12.12	3.12	.48
270	90	11.89		12.14	3.00	.46
280	100	11.91		12.16	2.80	.44
290	110	11.93		12.18	2.54	.42
300	120	11.95		12.20	2.50	.40
325	145	12.01		12.26	2.24	.34
345	165	12.05		12.30	2.08	.30
360	180	12.07		12.32	2.00	.28



Aquifer Test 7
Well Number 9-55-27bb
10^3
10^2
t/t'
10^1
10^0
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
s' feet
T = 264 Q / Δ s' = (264)(3.52) / 0.92
T = 1000 gpd/ft.

Log of well 9-55-9bd
(About 3 miles distant from tested well, 9-55-27bb)

Well owner, Mr. Shumaker

Log provided by George Askin, Miles City, Montana

Depth (feet) From	To	Thickness (feet)	
0	2	2	Soil
2	15	13	Gumbo, blue
15	17	2	Sand
17	35	18	Gumbo
35	36	1	Rock
36	105	69	Gumbo, blue and rock
105	111	6	Coal
111	245	134	Gumbo, blue and rock
245	260	15	Coal
260	480	220	Gumbo, blue and rock
480	500	20	Sand
500	680	180	Gumbo, blue
680	825	145	Sand and rock, hard
825	835	10	Gumbo

Assumed aquifer thickness 165 feet

Aquifer test 8 (Recovery test)

Well number 10-58-32db2 (Pumped well)

Well number 10-58-32db1 (Observation well)

February 2-3, 1962

Test conducted by Ross K. Petersen

Analysis by O. James Taylor

Average discharge, Q = 35 gpm r = 920 feet

Time t' (minutes)	r^2/t' (ft^2/min)	Depth to water (feet)	Recovery s-s' (feet)
0		224.2	
10		224.2	
20		224.2	
30		224.2	
40		224.2	
50		224.2	
60		224.2	
75		224.2	
90		224.2	
105		224.2	
120		224.2	
150		224.2	
180		224.2	
275	3.07×10^3	224.14	0.06
325	2.60×10^3	224.10	.10
360	2.35×10^3	224.06	.14
390	2.17×10^3	224.06	.14
455	1.86×10^3	224.00	.20
510	1.66×10^3	223.96	.24
565	1.50×10^3	223.92	.28
635	1.33×10^3	223.89	.31
690	1.22×10^3	223.82	.38
755	1.12×10^3	223.79	.41
1,020	8.30×10^2	223.55	.65
1,080	7.83×10^2	223.49	.71
1,200	7.03×10^2	223.42	.78
1,320	6.40×10^2	223.35	.85
1,380	6.12×10^2	223.31	.89
1,440	5.88×10^2	223.25	.95

Log of well 10-58-32db1

Well owner, Shell Oil Co.

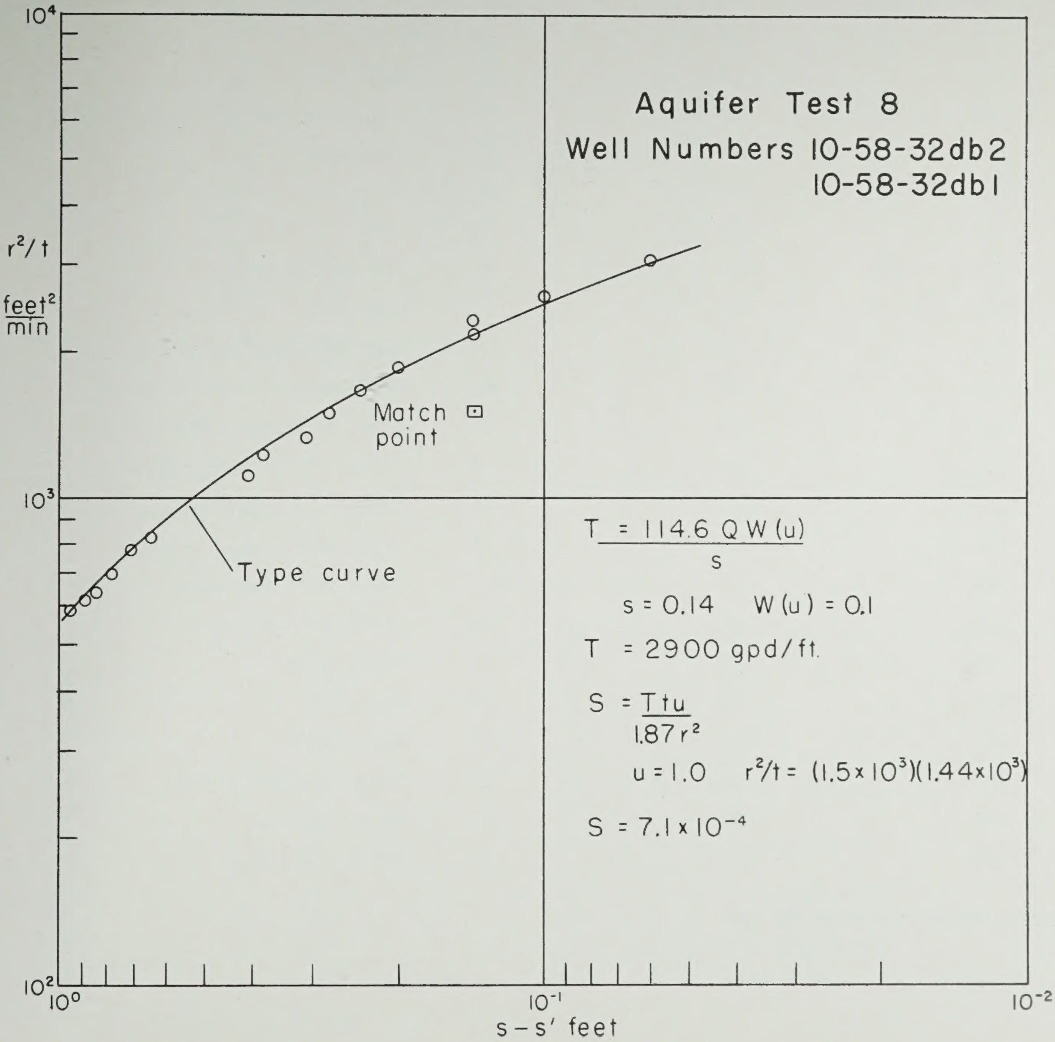
Log provided by Shell Oil Co., Billings, Montana

Depth (feet) From	To	Thickness (feet)	
0	4	4	Clay, yellow
4	5	1	Rock
5	70	65	Clay, gray
70	74	4	Rock
74	80	6	Clay, gray
80	81	1	Rock

Log of well 10-58-32db1—(Continued)

Depth (feet) From	To	Thickness (feet)	
81	280	199	Clay, gray
280	320	40	Sand and clay streaks
320	326	6	Sand
326	327	1	Rock
327	380	53	Sand, with water
380	418	38	Sand and clay streaks
418	440	22	Sand, with water
440	463	23	Shale

Assumed aquifer thickness 159 feet



Log of well 10-58-32db2

Well owner, Shell Oil Co.

Log provided by Shell Oil Co., Billings, Montana

Depth (feet)			
From	To	Thickness (feet)	
0	30	30	Clay
30	51	21	Clay
51	89	38	Clay with sandy streaks
89	94	5	Lime streak
94	99	5	Clay
99	124	25	Sand, silty
124	195	71	Clay, gray, light and dark streaks
195	205	10	Clay, sandy
205	223	18	Clay, gray
223	231	8	Sand
231	260	29	Clay, sandy, soft
260	271	11	Sand, silty
271	272	1	Lime, streaks, hard
272	293	21	Shale, gray, with hard streaks
293	323	30	Sand, with small shale streaks
323	332	9	Shale, with hard lime streaks
332	343	11	Shale, sticky, light gray
343	348	5	Shale, soft, sticky
348	353	5	Shale, hard, dark gray
353	395	42	Shale, soft, light gray
395	406	11	Sand, shaly
406	430	24	Sand, soft
430	437	7	Sand, shaly
437	450	13	Sand with clay streaks
450	466	16	Shale, sandy
466	497	31	Shale, sticky gray

Assumed aquifer thickness 168 feet

Aquifer test 9 (Drawdown test)
Well number 10-58-18cd (Pumped well)
Well number 10-58-18dc (Observation well)
July 30-August 4, 1963

Test conducted by O. James Taylor
Average discharge, Q = 53.5 gpm r = 670 feet
Static water level 140.93 feet

Time t (minutes)	r^2/t (ft^2/min)	Depth to water (feet)	Drawdown s (feet)
300	1.50×10^3	140.94	0.01
428	1.05×10^3	140.99	.06
480	9.35×10^2	141.03	.10
660	6.70×10^2	141.17	.24
720	6.22×10^2	141.22	.29
927	4.85×10^2	141.32	.39
960	4.69×10^2	141.33	.40
1,005	4.46×10^2	141.35	.42
1,130	3.98×10^2	141.39	.46
1,222	3.67×10^2	141.43	.50
1,500	3.00×10^2	141.47	.54
1,985	2.27×10^2	141.49	.56
2,358	1.91×10^2	141.51	.58
2,970	1.52×10^2	141.49	.56
3,708	1.21×10^2	141.63	.70
4,330	1.04×10^2	141.78	.85
7,845	5.73×10^1	141.67	.74

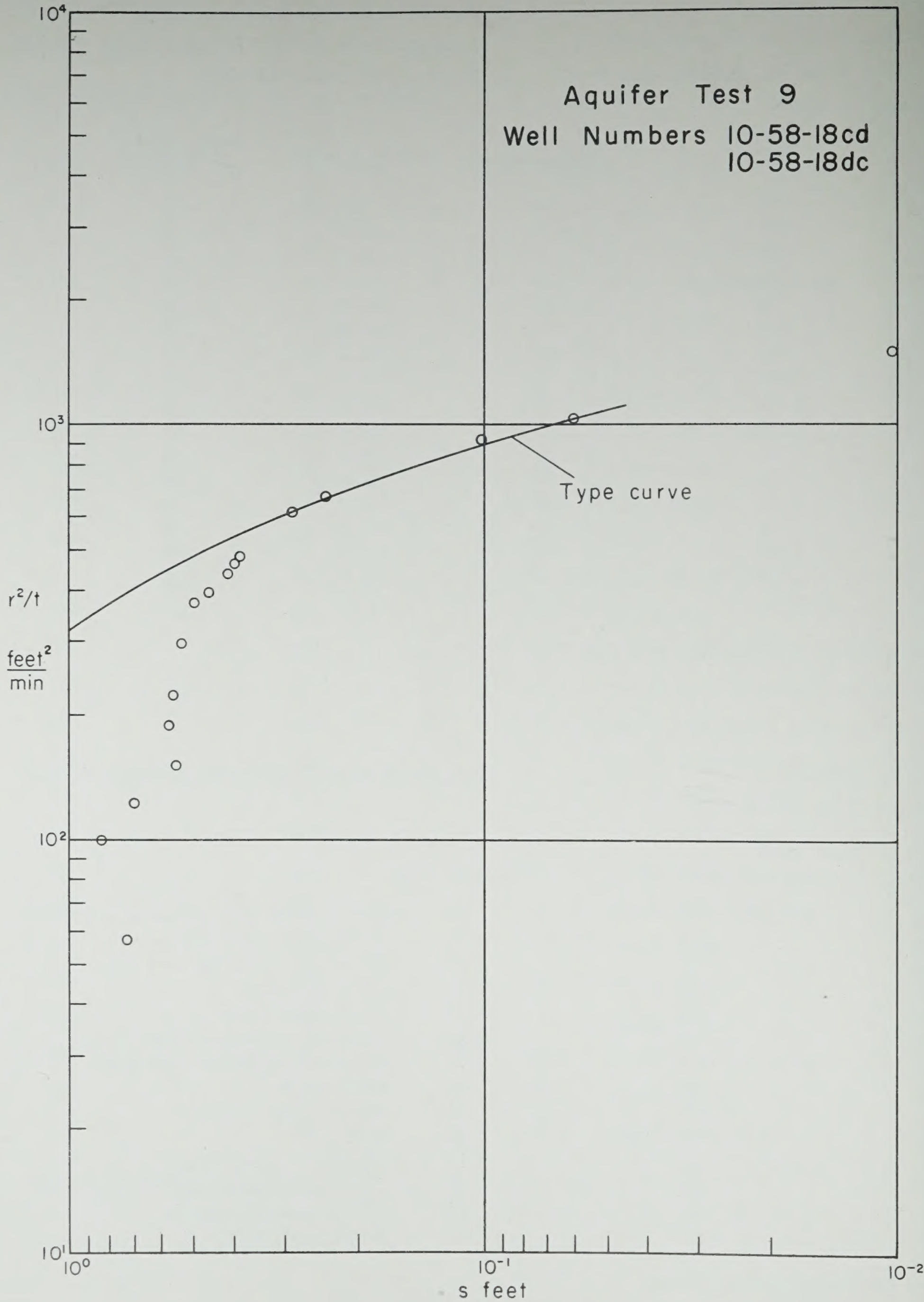
Note: Data given are those selected for plotting

Log of well 10-58-18cd
Well owner, Shell Oil Co.

Log provided by Shell Oil Co., Billings, Montana

Depth (feet) From	To	Thickness (feet)	
0	55	55	Shale, green and blue, coal and shells
55	80	25	Shale, gray, soft, clayey
80	98	18	Shale, green, sticky
98	148	50	Sand, dark gray
148	150	2	Shale, hard lime
150	190	40	Sand, dark gray, a little silty
190	200	10	Sand and claystone, dark gray
200	240	40	Clay, sandy
240	270	30	Sand, muddy and silty
270	300	30	Shale
300	310	10	Shales of various colors
310	350	40	Shale, gray and sticky
350	370	20	Shale, dark, and shells
370	395	25	Shale, blue, sticky

Assumed aquifer thickness 150 feet



Aquifer Test 9
Well Numbers 10-58-18cd
10-58-18dc
Type curve
10^4
10^3
10^2
10^1
r^2/t
$\frac{\text{feet}^2}{\text{min}}$
10^0
10^{-1}
10^{-2}
s feet

Aquifer test 10 (Flow test)

Well number 11-56-20aa

August 6, 1963

Test conducted by S. W. Lohman, Charles Lane, R. G. McMurtrey, and O. James Taylor

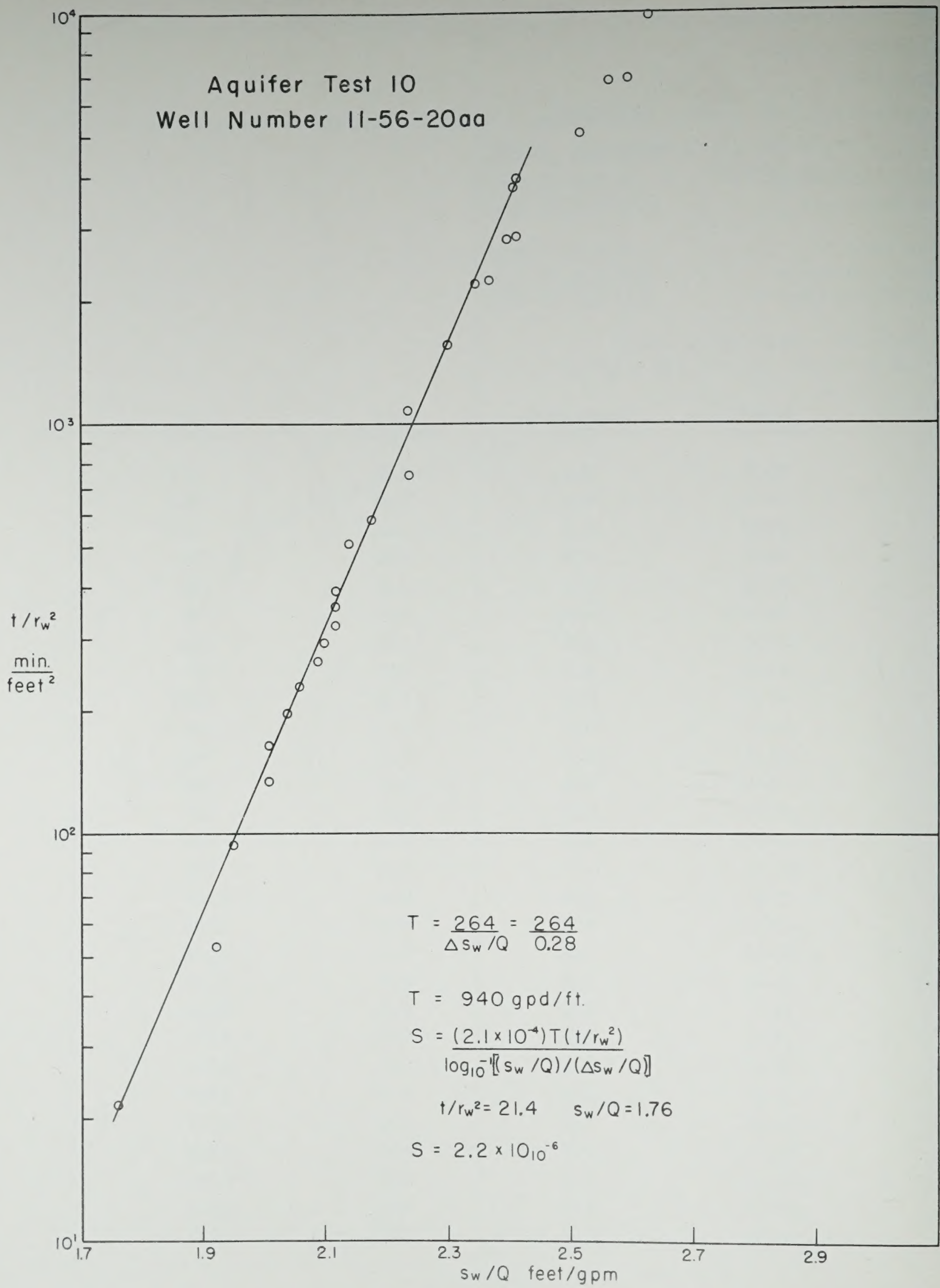
Static head	23.50 feet of water
Reservoir depression	+ .30 feet of water
Actual static head	23.80 feet of water

Flowing head	1.75 feet of water
Reservoir depression	+ 0.20 feet of water
Actual flowing head	1.95 feet of water

$s_w = 23.80 - 1.95 = 21.85$ feet of water.

$r_w = 1.25 \times 10^{-1}$ ft. $(r_w)^2 = 1.56 \times 10^{-2}$ ft^2

Time t (min-sec)	Discharge Q (gpm)	s_w/Q (feet/gpm)	$t/(r_w)^2$ (min/ft^2)
00-20	12.4	1.76	21.4
00-50	11.4	1.92	53.3
01-27	11.2	1.95	92.8
02-05	10.9	2.01	133
02-35	10.9	2.01	165
03-05	10.75	2.04	198
03-35	10.6	2.06	229
04-04	10.45	2.09	261
04-37	10.4	2.10	296
05-07	10.3	2.12	328
05-38	10.3	2.12	360
06-08	10.3	2.12	393
07-57	10.2	2.14	509
09-13	10.0	2.18	590
11-48	9.75	2.24	755
17-00	9.75	2.24	1,088
24-17	9.50	2.30	1,553
34-17	9.30	2.35	2,200
34-46	9.20	2.37	2,230
44-11	9.10	2.40	2,820
44-50	9.05	2.41	2,870
59-20	9.05	2.41	3,800
59-55	9.05	2.41	3,840
79-24	8.65	2.52	5,090
106-45	8.50	2.57	6,830
107-25	8.40	2.60	6,875
152-07	8.30	2.63	9,740
181-56	8.25	2.65	11,680


Aquifer Test 10
Well Number 11-56-20aa
10^4
10^3
10^2
10^1
t / r_w^2
$\frac{\text{min.}}{\text{feet}^2}$
1.7
1.9
2.1
2.3
2.5
2.7
2.9
s_w / Q feet/gpm
$T = \frac{264}{\Delta s_w / Q} = \frac{264}{0.28}$
T = 940 gpd/ft.
$S = \frac{(2.1 \times 10^{-4}) T (t/r_w^2)}{\log_{10}^{-1}[(s_w/Q)/(\Delta s_w/Q)]}$
$t/r_w^2 = 21.4$ $s_w/Q = 1.76$
$S = 2.2 \times 10_{10}^{-6}$

Aquifer test 11 (Flow recovery test)

Well number 11-56-20aa

August 9, 1963

Test conducted by S. W. Lohman, Charles Lane, R. G. McMurtrey, and O. James Taylor

Static head 23.80 feet of water

Average discharge, Q = 9.0 gpm

Time t (minutes)	Time t′ (minutes)	Head (feet of water)	Reservoir depression (feet of water)	Adjusted head h′ (feet of water)	t/t′
201	1	16.80		17.10	201
202	2	17.42		17.72	101
203	3	17.81	0.30	18.01	67.7
204	4	18.07		18.37	51.0
205	5	18.25		18.55	41.0
206	6	18.45		18.75	34.3
207	7	18.57		18.87	29.6
209	9	18.79		19.09	23.2
212	12	19.05	.30	19.35	17.7
217	17	19.40		19.70	12.8
222	22	19.68	.30	19.98	10.1
230	30	20.00		20.30	7.67
240	40	20.29		20.59	6.00
250	50	20.52		20.82	5.00
260	60	20.71		21.01	4.33

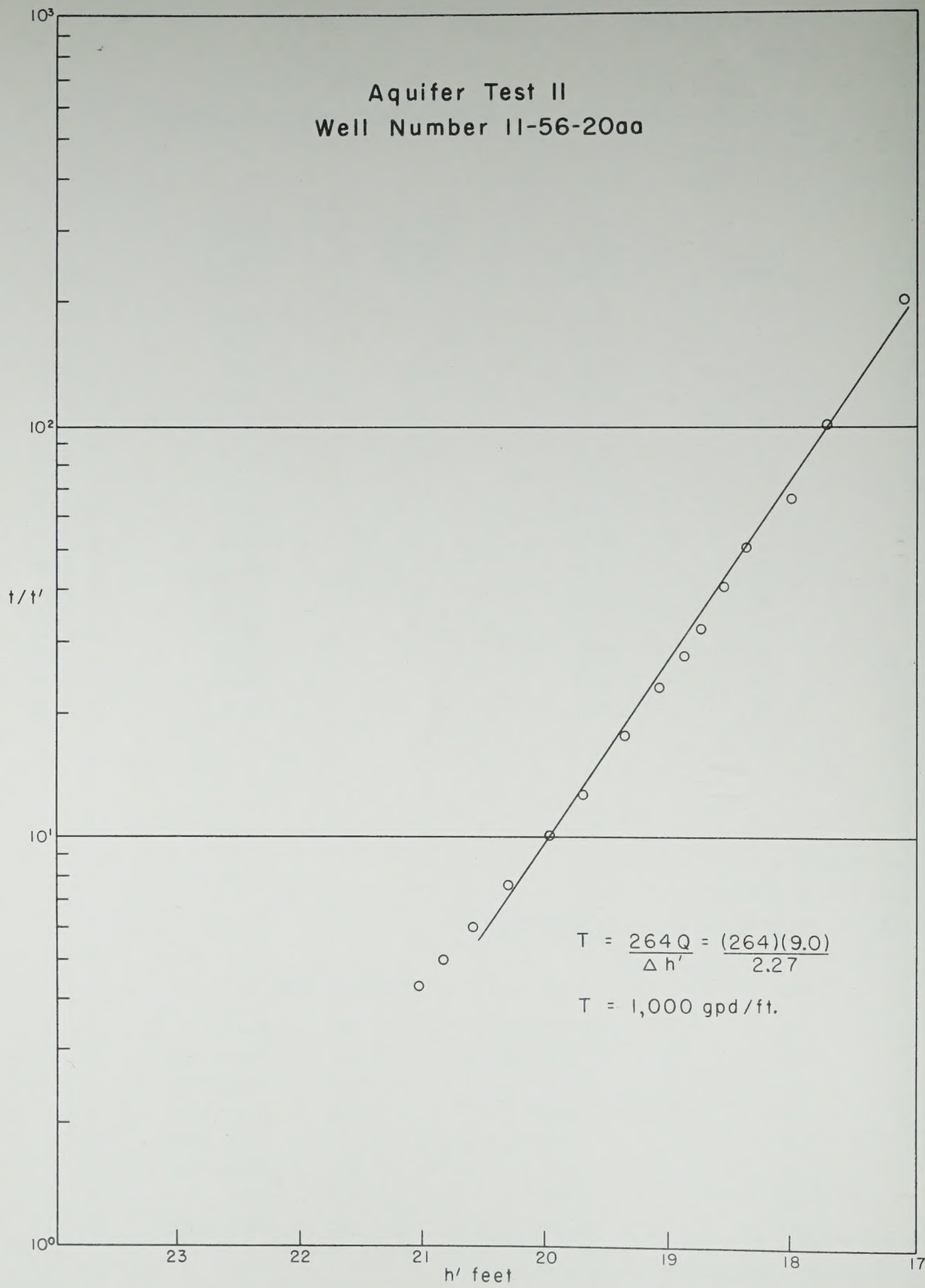
Log of well 11-56-20aa

Well owner, Mr. Ole Seteren

Log provided by Frank Bandy, Jr., Broadus, Montana

Depth (feet) From	To	Thickness (feet)	
0	63	63	Sand
63	398	335	Shale, blue
398	400	2	Rock, hard
400	529	129	Shale, blue
529	536	7	Rock, hard
536	880	344	Shale, blue
880	1,152	272	Sand
1,152	1,180	28	Shale, gray

Assumed aquifer thickness 272 feet


Aquifer Test II
Well Number 11-56-20aa
10^3
10^2
10^1
10^0
t/t′
T = 264 Q / Δ h′ = (264)(9.0) / 2.27
T = 1,000 gpd/ft.
23
22
21
20
19
18
17
h′ feet

Aquifer test 12 (Single well drawdown test)

Well number 11-57-6cc

March 5-9, 1962

Test conducted by Ross K. Petersen

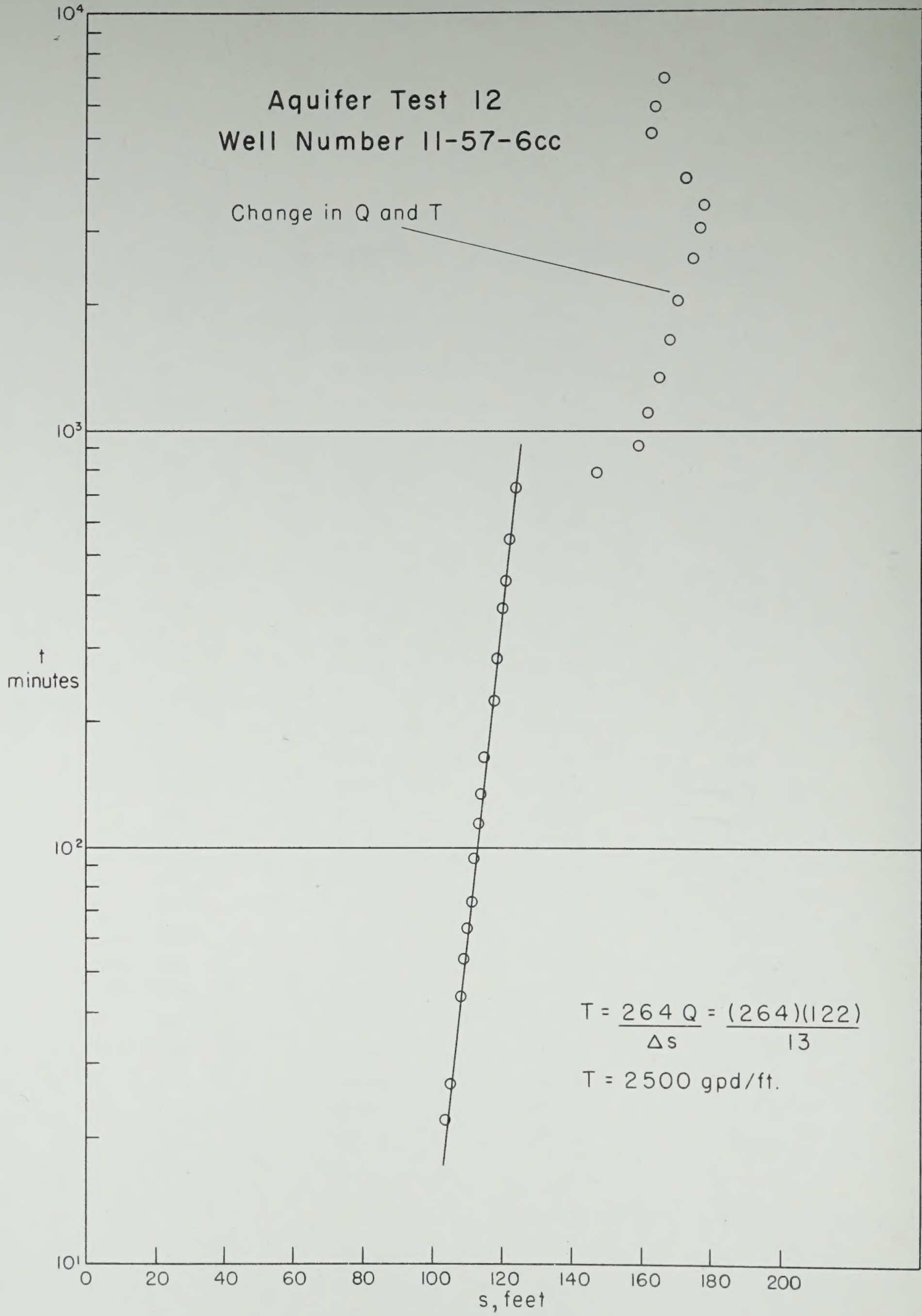
Analysis by O. James Taylor

Static water level 310.00 feet

Discharge, Q = 150-107 gpm

Time t (minutes)	Depth to water (feet)	Drawdown s (feet)	Discharge Q (gpm)
22	414.66	104.66	132
27	415.68	105.68	
44	418.16	108.16	133
54	419.16	109.16	132
64	430.25	110.25	
74	421.08	111.08	131
94	422.42	112.42	
114	423.54	113.54	
134	424.29	114.29	
164	425.68	115.68	
224	427.92	117.92	
284	429.16	119.16	
374	430.42	120.42	
434	431.50	121.50	
554	433.00	123.00	115
736	441.66	131.66	150
794	456.92	146.92	140
914	468.92	158.92	147
1,094	471.75	161.75	147
1,334	475.50	165.50	145
1,634	478.08	168.08	145
2,054	480.33	170.33	142
2,534	484.58	174.58	142
3,014	486.25	176.25	140
3,494	487.75	177.75	136
4,004	473.25	163.25	112
5,054	471.92	161.92	112
5,954	473.66	163.66	
6,974	476.58	166.58	112

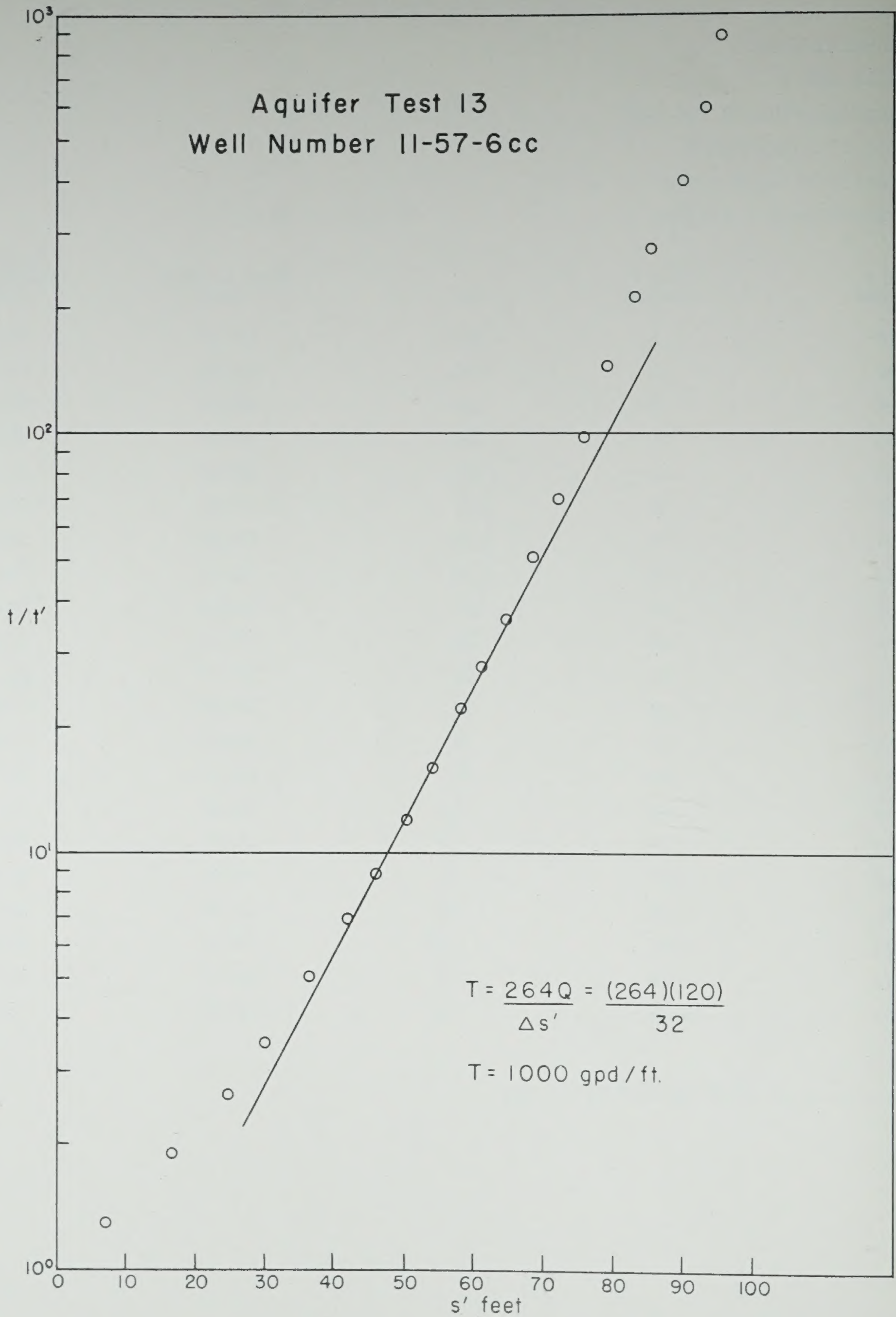
Note: Data given are those selected for plotting


Aquifer Test 12
Well Number 11-57-6cc
Change in Q and T
$T = \frac{264\,Q}{\Delta s} = \frac{(264)(122)}{13}$
T = 2500 gpd/ft.
t
minutes
10^4
10^3
10^2
10^1
0
20
40
60
80
100
120
140
160
180
200
s, feet

Aquifer test 13 (Single well recovery test)
Well number 11-57-6cc
March 10-23, 1962
Test conducted by Ross K. Petersen
Analysis by O. James Taylor
Static water level 310.00 feet
Average discharge, Q = 120 gpm

Time t (minutes)	Time t′ (minutes)	t/t′	Depth to water (feet)	Residual drawdown s′ (feet)
7,158	6	895	405.42	95.42
7,162	12	596	403.33	93.33
7,168	18	398	399.33	89.33
7,176	26	276	395.33	85.33
7,184	34	211	392.92	82.92
7,198	49	147	389.00	79.00
7,224	74	98	385.50	75.50
7,254	104	70	382.16	72.16
7,294	144	51	378.58	68.58
7,354	204	36	374.50	64.50
7,414	234	28	371.08	61.08
7,494	344	22	368.33	58.33
7,634	484	16	363.92	53.92
7,814	664	12	360.50	50.50
8,054	904	8.9	355.92	45.92
8,354	1,204	7.0	351.92	41.92
8,954	1,804	5.0	346.50	36.50
10,034	2,834	3.5	339.74	29.74
11,474	4,324	2.66	334.50	24.50
14,879	7,729	1.9	326.78	16.78
25,400	19,249	1.3	316.48	6.48

Note: Data given are those selected for plotting


Aquifer Test 13
Well Number 11-57-6cc
$T = \frac{264Q}{\Delta s'} = \frac{(264)(120)}{32}$
T = 1000 gpd/ft.
t/t'
10^3
10^2
10^1
10^0
0
10
20
30
40
50
60
70
80
90
100
s' feet

Log of well 11-57-6cc

Well owner, Shell Oil Co.

Log provided by Shell Oil Co.

Depth (feet) From	Depth (feet) To	Thickness (feet)	
0	5	5	Soil
5	54	49	Shale
54	82	28	Shale, gray, and coal
82	85	3	Coal
85	103	18	Shale, coal lens
103	105	2	Coal
105	313	208	Shale and coal
313	328	15	Sand, fine, dirty
328	383	55	Sand, fine, gray, clean
383	388	5	Shale, blue
388	393	5	Sand, gray
393	410	17	Shale, gray
410	417	7	Sand, gray
417	623	206	Shale and coal
623	632	9	Shale and sand
632	1,002	370	Shale and coal
1,002	1,019	17	Shale and sandstone
1,019	1,109	90	Shale and coal
1,109	1,118	9	Sandstone, gray-green, fine, soft
1,118	1,120	2	Shale
1,120	1,132	12	Sandstone
1,132	1,156	24	Shale, sandy, soft
1,156	1,178	22	Sandstone
1,178	1,182	4	Shale
1,182	1,233	51	Sandstone
1,233	1,248	15	Sandstone lens
1,248	1,253	5	Sandstone, dirty
1,253	1,263	10	Shale, hard

Assumed aquifer thickness 135 feet (Gamma log = 150 feet)

Note: Screen and filter sand installed from 1,104 feet to 1,253 feet

Aquifer test 14 (Flow test)

Well number 12-55-36dd

August 8, 1963

Test conducted by R. G. McMurtrey and O. James Taylor

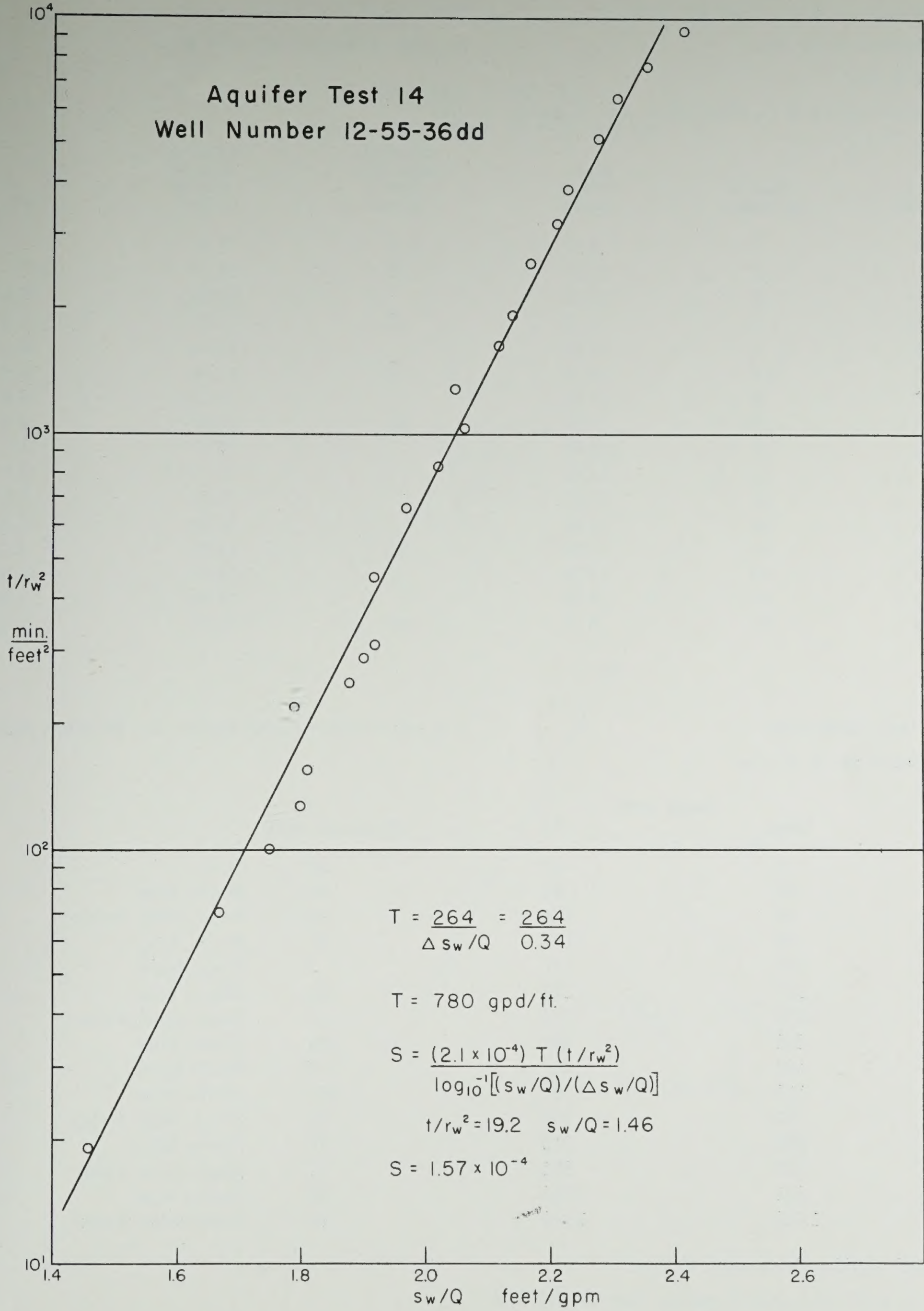
Static head	18.17 feet of water
Reservoir depression	+ 0.40 feet of water
Actual static head	18.57 feet of water

Flowing head	2.22 feet of water
Reservoir depression	+ 0.25 feet of water
Actual flowing head	2.47 feet of water

s_w = 18.57-2.47 = 16.10 feet of water

$r_w = 1.25 \times 10^{-1}$ ft. $(r_w)^2 = 1.56 \times 10^{-2}$ ft^2

Time t (min-sec)	Discharge Q (gpm)	s_w/Q (feet/gpm)	$t/(r_w)^2$ (min/ft^2)
00-18	11.0	1.46	19.2
01-06	9.65	1.67	70.3
01-33	9.19	1.75	99.0
02-00	8.95	1.80	128
02-25	8.88	1.81	154
03-27	9.00	1.79	220
03-55	8.55	1.88	250
04-30	8.45	1.90	288
04-52	8.39	1.92	310
07-01	8.39	1.92	449
10-22	8.18	1.97	661
13-06	7.99	2.02	835
16-00	7.80	2.06	1,020
20-00	7.89	2.05	1,280
25-02	7.59	2.12	1,620
30-01	7.50	2.14	1,917
40-00	7.42	2.17	2,560
50-00	7.30	2.21	3,200
60-40	7.20	2.23	3,880
79-55	7.05	2.28	5,110
100-15	6.95	2.31	6,390
120-45	6.82	2.36	7,670
145-33	6.66	2.42	9,310


Aquifer Test 14
Well Number 12-55-36dd
10^4
10^3
10^2
10^1
t/r_w^2
$\frac{\text{min.}}{\text{feet}^2}$
$T = \frac{264}{\Delta s_w/Q} = \frac{264}{0.34}$
T = 780 gpd/ft.
$S = \frac{(2.1 \times 10^{-4})\ T\ (t/r_w^2)}{\log_{10}^{-1}[(s_w/Q)/(\Delta s_w/Q)]}$
$t/r_w^2 = 19.2 \quad s_w/Q = 1.46$
$S = 1.57 \times 10^{-4}$
1.4
1.6
1.8
2.0
2.2
2.4
2.6
s_w/Q feet/gpm

Aquifer test 15 (Flow recovery test)

Well number 12-55-36dd

August 8, 1963

Test conducted by R. G. McMurtrey and O. James Taylor

Static head 18.57 feet of water

Average discharge, Q = 7.2 gpm

Time t (minutes)	Time t′ (minutes)	Head (feet of water)	Reservoir depression (feet of water)	Adjusted head h′ (feet of water)	t/t′
150	0	2.22	0.25	2.47	
151	1	12.77	.35	13.12	151
152	2	13.28		13.63	76.0
153	3	13.60	.35	13.95	51.0
154	4	13.82		14.18	38.5
156	6	14.11	.38	14.49	26.0
158	8	14.34		14.72	19.8
160	10	14.55	.38	14.93	16.0
162	12	14.69		15.07	13.5
165	15	14.90		15.28	11.0
170	20	15.13		15.51	8.50
180	30	15.42		15.80	6.00
190	40	15.63	.38	16.01	4.75
200	50	15.79		16.17	4.00
210	60	15.92		16.30	3.50
230	80	16.15	.40	16.55	2.88

Log of well 12-55-36dd

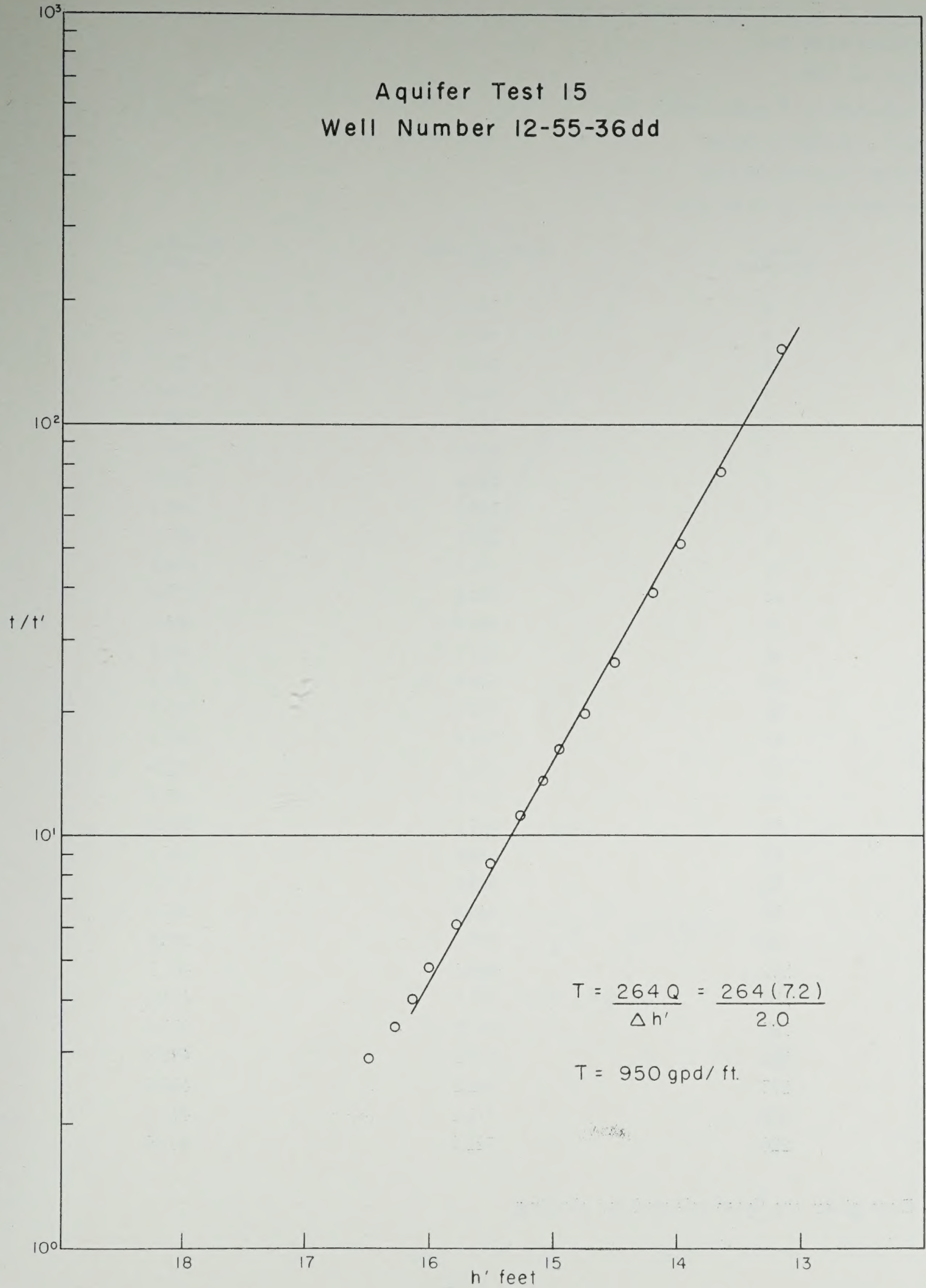
Well owner, Dave Strobel

Log provided by Frank Bandy, Jr., Broadus, Montana

Depth (feet) From	To	Thickness (feet)	
0	16	16	Soil
16	94	78	Shale, blue
94	123	29	Sand, with water
123	184	61	Shale, blue
184	187	3	Rock, hard
187	340	153	Shale, blue
340	362	22	Sand, with water
362	507	145	Shale, blue
507	510	3	Rock, hard
510	793	283	Shale, blue
793	840	47	Sand, with water
840	910	70	Shale, blue
910	921	11	Sand, with water
921	1,010	89	Shale, blue
1,010	1,100	90	Sand, with water

Assumed aquifer thickness 148 feet.

Cased to 1,087 with 2-inch casing. Seat at 625 feet.


Aquifer Test 15
Well Number 12-55-36dd
10^3
10^2
10^1
10^0
t/t'
T = 264 Q / Δh' = 264 (7.2) / 2.0
T = 950 gpd/ft.
18
17
16
15
14
13
h' feet

Aquifer test 16 (Single well drawdown test)

Well number 12-56-25cb

November 17, 1962

Test conducted by Frederickson's Inc.

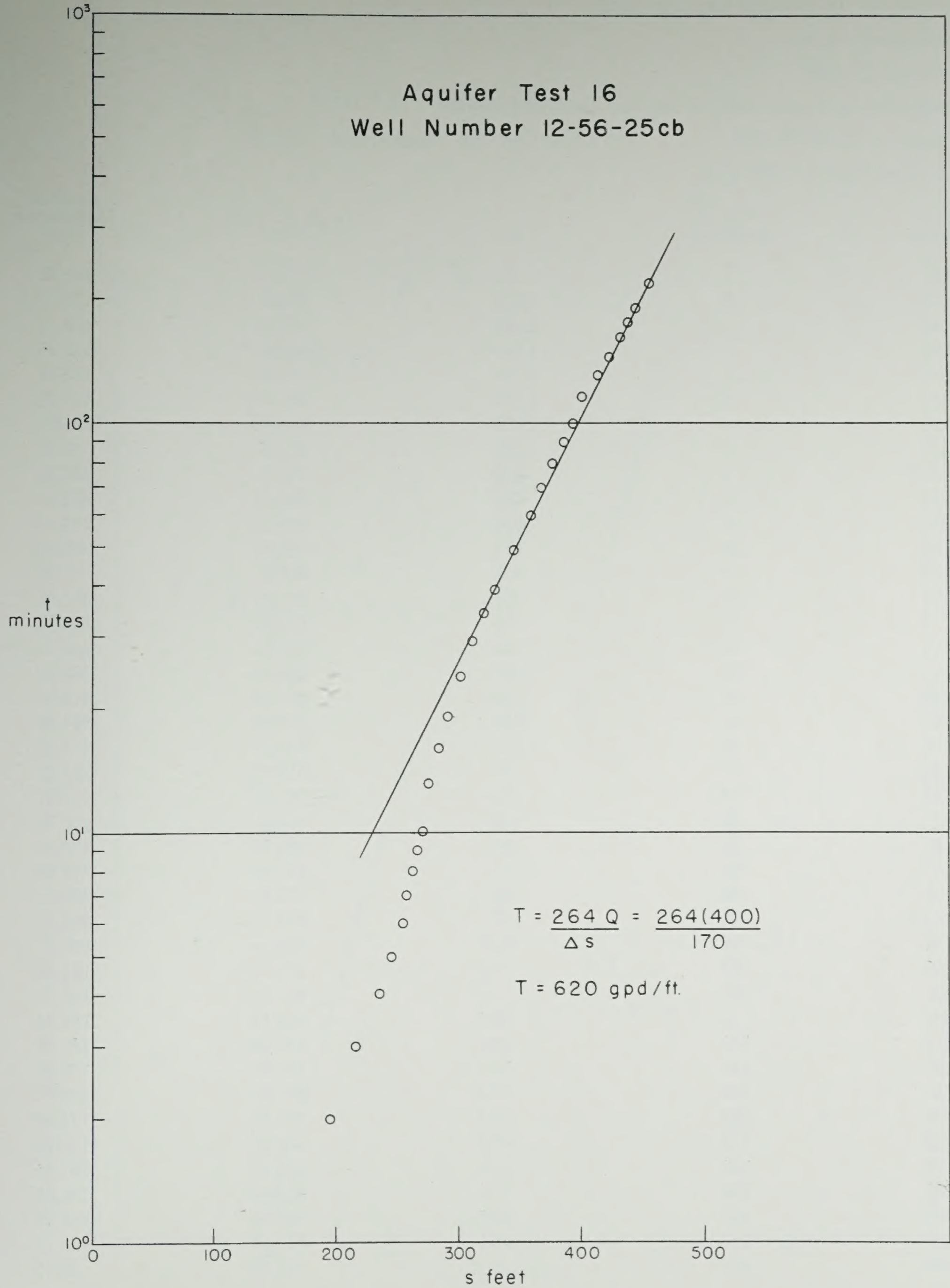
Analysis by O. James Taylor

Static water level 263.85 feet

Average discharge, Q = 400 gpm

Time t (minutes)	Depth to water (feet)	Drawdown s (feet)
1	370.1	106.2
2	460.2	196.3
3	481.1	217.2
4	498.9	235.0
5	510.1	246.2
6	517.8	253.9
7	521.9	258.0
8	526.1	262.2
9	529.1	265.2
10	534.1	270.2
13	540.3	276.4
16	548.4	284.5
19	554.8	290.9
24	565.8	301.9
29	575.4	311.5
34	585.4	321.5
39	592.8	328.9
49	611.2	347.3
59	624.1	360.2
69	633.6	369.7
79	642.2	378.3
89	649.8	385.9
99	657.8	393.9
115	665.1	401.2
130	678.5	414.6
145	687.5	423.6
160	696.2	432.3
175	702.8	438.9
190	711.4	447.5
220	721.8	457.9

Note: Data given are those selected for plotting.


Aquifer Test 16
Well Number 12-56-25cb
10^3
10^2
10^1
10^0
t
minutes
$T = \frac{264\ Q}{\Delta s} = \frac{264(400)}{170}$
T = 620 gpd/ft.
0
100
200
300
400
500
s feet

Aquifer test 17 (Single well recovery test)

Well number 12-56-25cb

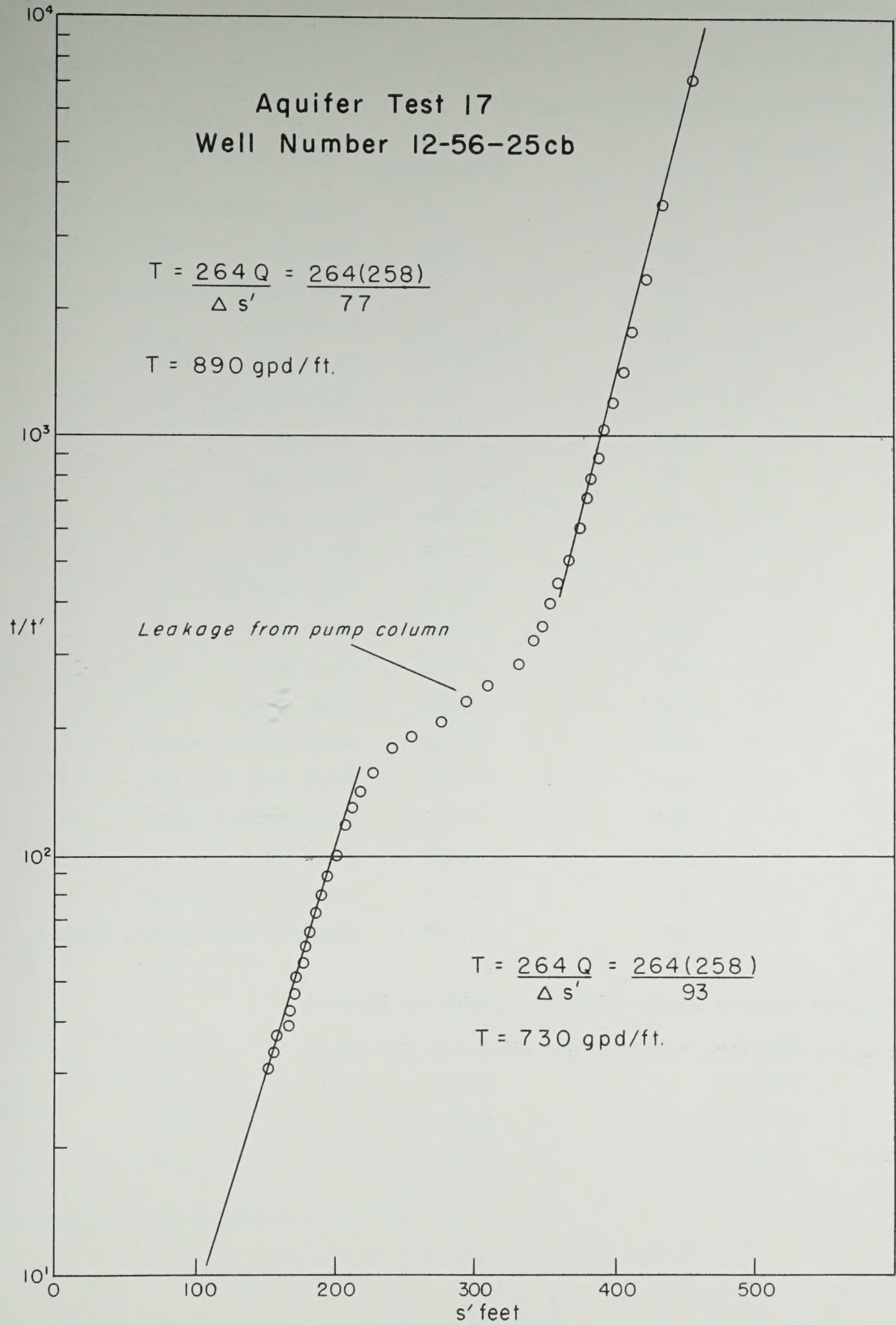
November 22-23, 1962

Test conducted by Frederickson's Inc. and O. James Taylor

Static water level 263.85 feet

Average discharge, Q = 258 gpm

Time t (minutes)	Time t′ (minutes)	t/t′	Depth to water (feet)	Residual drawdown s′ (feet)
7,193	1	7,193	720.7	456.85
7,194	2	3,597	699.1	435.25
7,195	3	2,398	687.25	423.40
7,196	4	1,798	677.8	413.95
7,197	5	1,439	670.86	407.01
7,198	6	1,199	664.17	400.32
7,199	7	1,028	658.48	394.63
7,200	8	900	653.4	389.55
7,201	9	800	649.15	385.30
7,202	10	720	646.25	382.40
7,204	12	600	638.22	374.37
7,206	14	515	630.85	367.00
7,208	16	451	624.6	360.75
7,210	18	401	618.85	355.00
7,212	20	361	613.55	349.70
7,214	22	328	608.50	344.65
7,217	25	289	596.08	332.23
7,220	28	258	574.15	310.30
7,223	31	233	557.91	294.06
7,226	34	212	542.77	278.92
7,229	37	195	518.00	254.15
7,232	40	181	505.06	241.21
7,237	45	161	492.20	228.35
7,242	50	145	484.40	220.55
7,247	55	131	478.40	214.55
7,252	60	121	472.85	209.00
7,262.7	70.7	103	466.40	202.55
7,272	80	90.9	459.85	196.00
7,282	90	80.9	455.43	191.58
7,292	100	72.9	451.55	187.70
7,302	110	66.4	448.19	184.34
7,312	120	60.9	444.86	181.01
7,322	130	56.3	441.85	178.00
7,332	140	52.3	437.66	173.81
7,347	155	47.3	435.45	171.60
7,362	170	43.3	432.00	168.15
7,377	185	39.9	431.50	167.65
7,392	200	36.9	423.83	159.98
7,407	215	34.5	402.08	156.23
7,422	240	30.9	416.00	152.15
8,562	1,370	6.25	350.00	86.15


Aquifer Test 17
Well Number 12-56-25cb
T = 264 Q / Δ s' = 264(258) / 77
T = 890 gpd/ft.
Leakage from pump column
T = 264 Q / Δ s' = 264(258) / 93
T = 730 gpd/ft.
t/t'
10⁴
10³
10²
10¹
0
100
200
300
400
500
s' feet

Log of well 12-56-25cb

Well owner, Shell Oil Co.

Log provided by Shell Oil Co., Billings, Montana

Depth (feet) From	To	Thickness (feet)	
0	60	60	Surface material
60	560	500	Shale, blue
560	592	32	Sand, gray
592	621	29	Shale, blue
621	652	31	Sand, gray
652	700	48	Shale, blue-gray
700	724	24	Sand, gray
724	821	97	Shale, blue
821	865	44	Sand, gray
865	960	95	Shale, gray
960	971	11	Coal, black
971	1,003	32	Shale, gray
1,003	1,031	28	Sand, gray
1,031	1,145	114	Shale, gray
1,145	1,182	37	Sand, salt and pepper
1,182	1,203	21	Shale, gray blue
1,203	1,326	123	Sand, salt and pepper
1,326	1,346	20	Shale, blue
1,346	1,410	64	Sand, salt and pepper
1,410	1,480	70	Sand and shale, lensed, dirty

Assumed aquifer thickness 259 feet (Gamma log thickness 270 feet)

Note: Screen and filter sand installed from 1,145 feet to 1,410 feet.

Aquifer test 18 (Single well drawdown test)

Well number 12-56-23cc

October 13-18, 1962

Test conducted by Frederickson's, Inc.

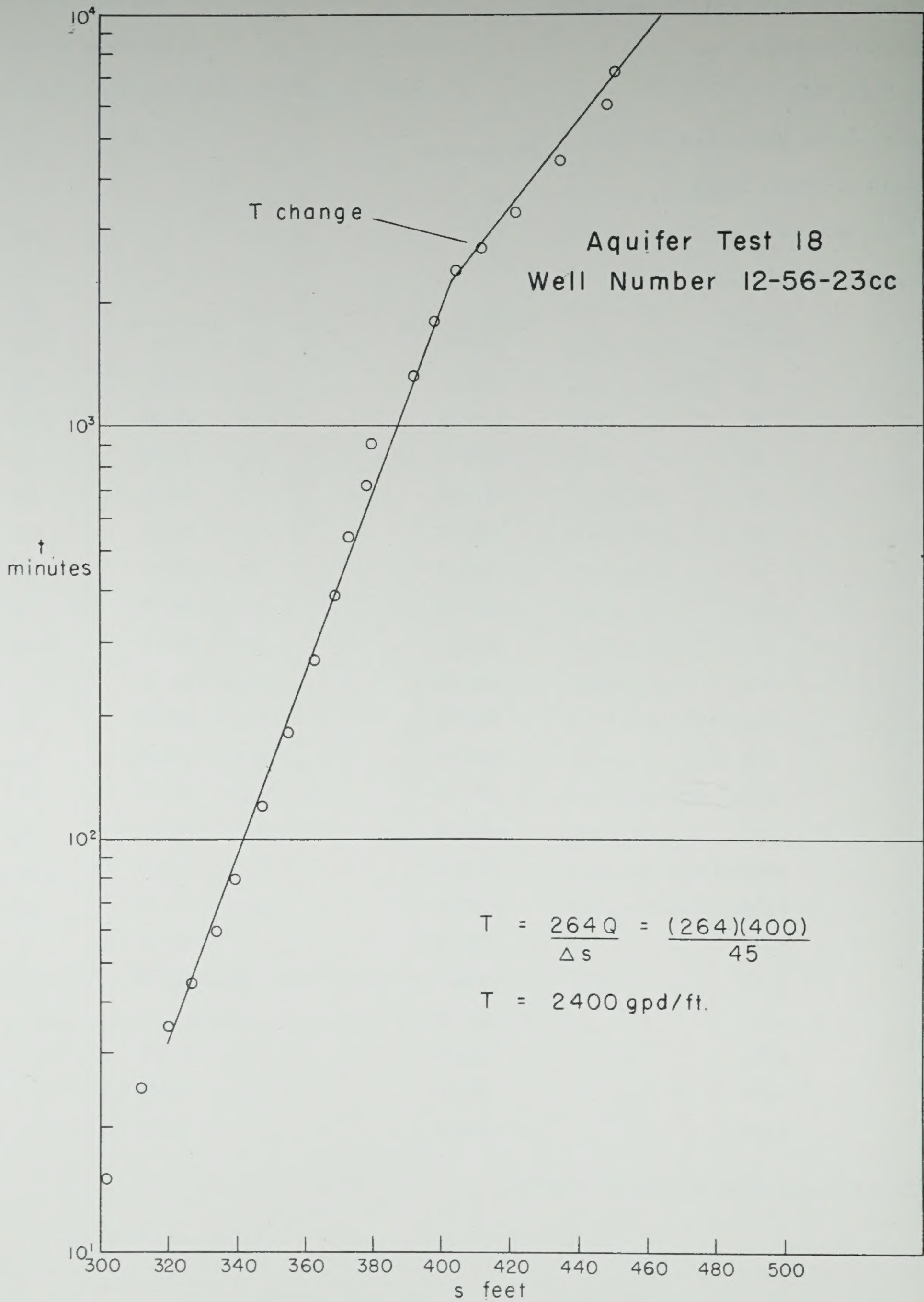
Analysis by O. James Taylor

Static water level 188.00 feet

Discharge, Q = 400-373 gpm

Time t (minutes)	Depth to water (feet)	Drawdown s (feet)
15	490.3	302.3
25	500.46	312.46
35	507.97	319.97
45	514.68	326.68
60	521.37	333.37
80	527.15	339.15
120	535.18	347.18
180	543.50	355.50
270	550.75	362.75
390	556.68	368.68
540	561.00	373.00
720	565.80	377.80
900	568.50	380.50
1,320	580.00	592.00
1,800	586.25	398.25
2,400	592.00	404.00
2,700	600.47	412.47
3,300	609.90	421.90
4,380	622.85	434.65
6,000	635.50	447.50
7,200	638.34	450.34

Note: Data given are those selected for plotting.



Aquifer Test 18
Well Number 12-56-23cc
T change
$T = \frac{264Q}{\Delta s} = \frac{(264)(400)}{45}$
T = 2400 gpd/ft.
t minutes
10^4
10^3
10^2
10^1
300 320 340 360 380 400 420 440 460 480 500
s feet

Aquifer test 19 (Single well recovery test)

Well number 12-56-23cc

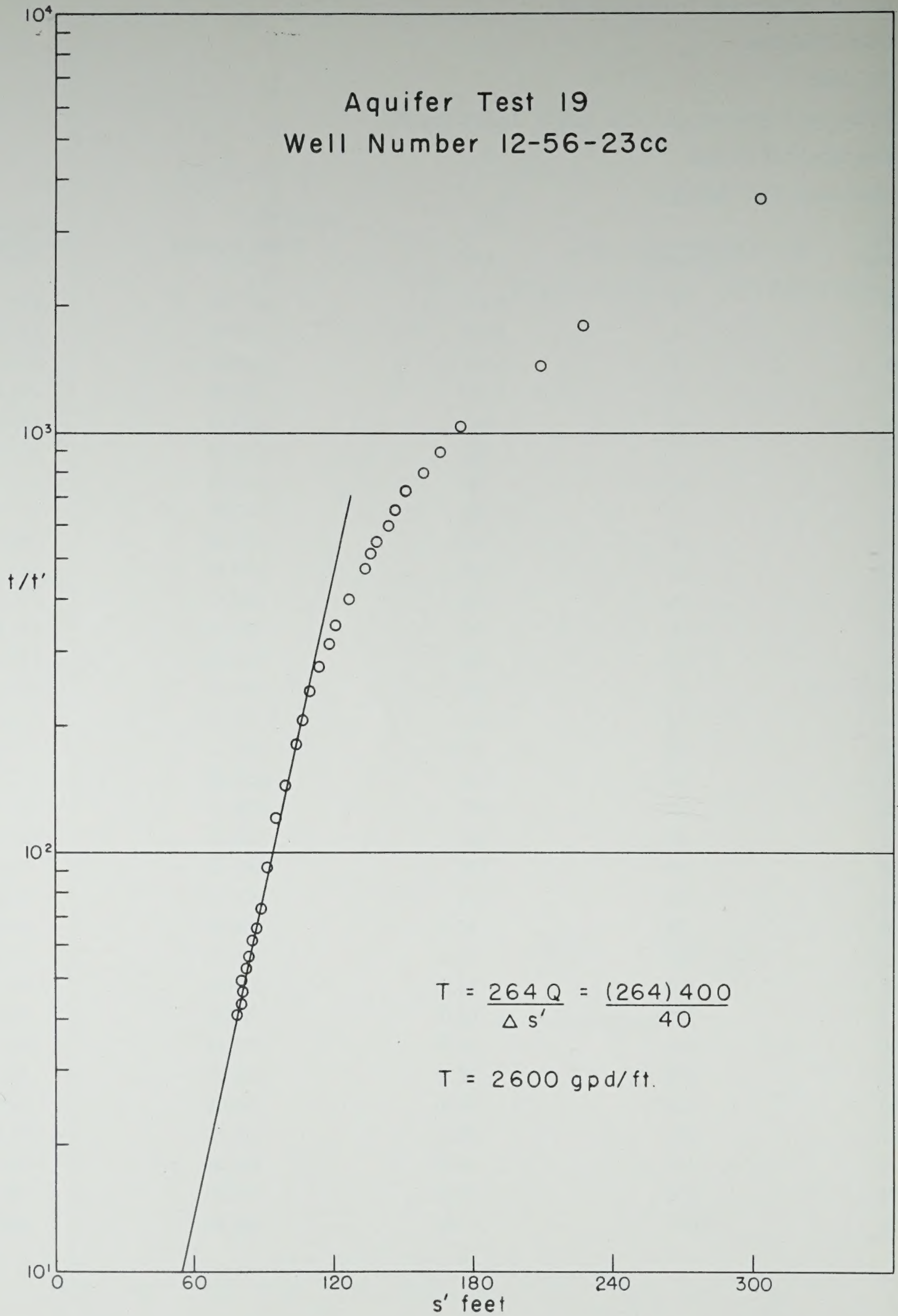
October 18, 1962

Test conducted by Frederickson's, Inc. and O. James Taylor

Static water level 188.40 feet

Average discharge, Q = 400 gpm

Time t (minutes)	Time t′ (minutes)	t/t′	Depth to water (feet)	Residual drawdown s′ (feet)
7,202	2	3,601	491.97	303.57
7,204	4	1,801	416.03	227.63
7,205	5	1,441	397.90	209.50
7,207	7	1,029	362.56	174.16
7,208	8	901	353.58	165.18
7,209	9	801	346.50	158.10
7,210	10	721	340.76	152.36
7,211	11	655	335.86	147.46
7,212	12	601	331.49	143.09
7,213	13	555	327.94	139.54
7,214	14	515	324.61	136.21
7,215	15	481	322.00	133.60
7,218	18	401	314.75	126.35
7,221	21	344	309.50	121.10
7,223	23	314	306.75	118.35
7,226	26	278	302.22	113.82
7,230	30	241	299.44	111.04
7,235	35	207	295.93	107.53
7,240	40	181	292.88	104.48
7,250	50	145	288.28	99.88
7,260	60	121	284.76	96.36
7,280	80	91.0	279.42	91.02
7,300	100	73.0	276.72	88.32
7,310	110	66.5	275.18	86.78
7,320	120	61.0	273.78	85.38
7,330	130	56.3	271.54	83.14
7,340	140	52.4	270.20	81.80
7,350	150	49.0	269.18	80.78
7,360	160	46.0	268.05	79.65
7,370	170	43.3	267.46	79.06
7,380	180	41.0	266.61	78.21
8,280	1,080	7.67	238.48	50.08


Aquifer Test 19
Well Number 12-56-23cc
10^4
10^3
10^2
10^1
t/t′
0
60
120
180
240
300
s′ feet
$T = \frac{264\,Q}{\Delta s'} = \frac{(264)\,400}{40}$
T = 2600 gpd/ft.

Log of well 12-56-23cc

Well owner, Shell Oil Co.

Log provided by Shell Oil Co., Billings, Montana

Depth (feet) From	To	Thickness (feet)	
0	61	61	Clay, yellow
61	67	6	Coal, black
67	160	93	Shale, gray
160	170	10	Shale, green
170	177	7	Sand
177	220	43	Shale, green
220	247	27	Shale, gray
247	380	133	Shale lensed with coal
380	550	170	Shale, gray
550	570	20	Coal, black
570	595	25	Shale, gray
595	610	15	Shale, gray
610	833	223	Shale, gray; lensed with coal
833	837	4	Shale, gray
837	910	73	Shale, gray
910	922	12	Shale, gray
922	985	63	Shale, gray
985	1,005	20	Shale, gray, soft with coal
1,005	1,076	71	Shale, gray, lensed with coal
1,076	1,082	6	Sand
1,082	1,100	18	Shale, gray
1,100	1,160	60	Sand, gray and white
1,160	1,180	20	Shale, gray
1,180	1,310	130	Sand, gray and white
1,310	1,380	70	Shale and sand
1,380	1,449	69	Shale, black

Assumed aquifer thickness 225 feet (gamma log thickness 480 feet)

Note: Screen and filter sand installed 1,100 feet to 1,310 feet.

Aquifer test 20 (Flow test)

Well number 12-56-19cd

August 11, 1963

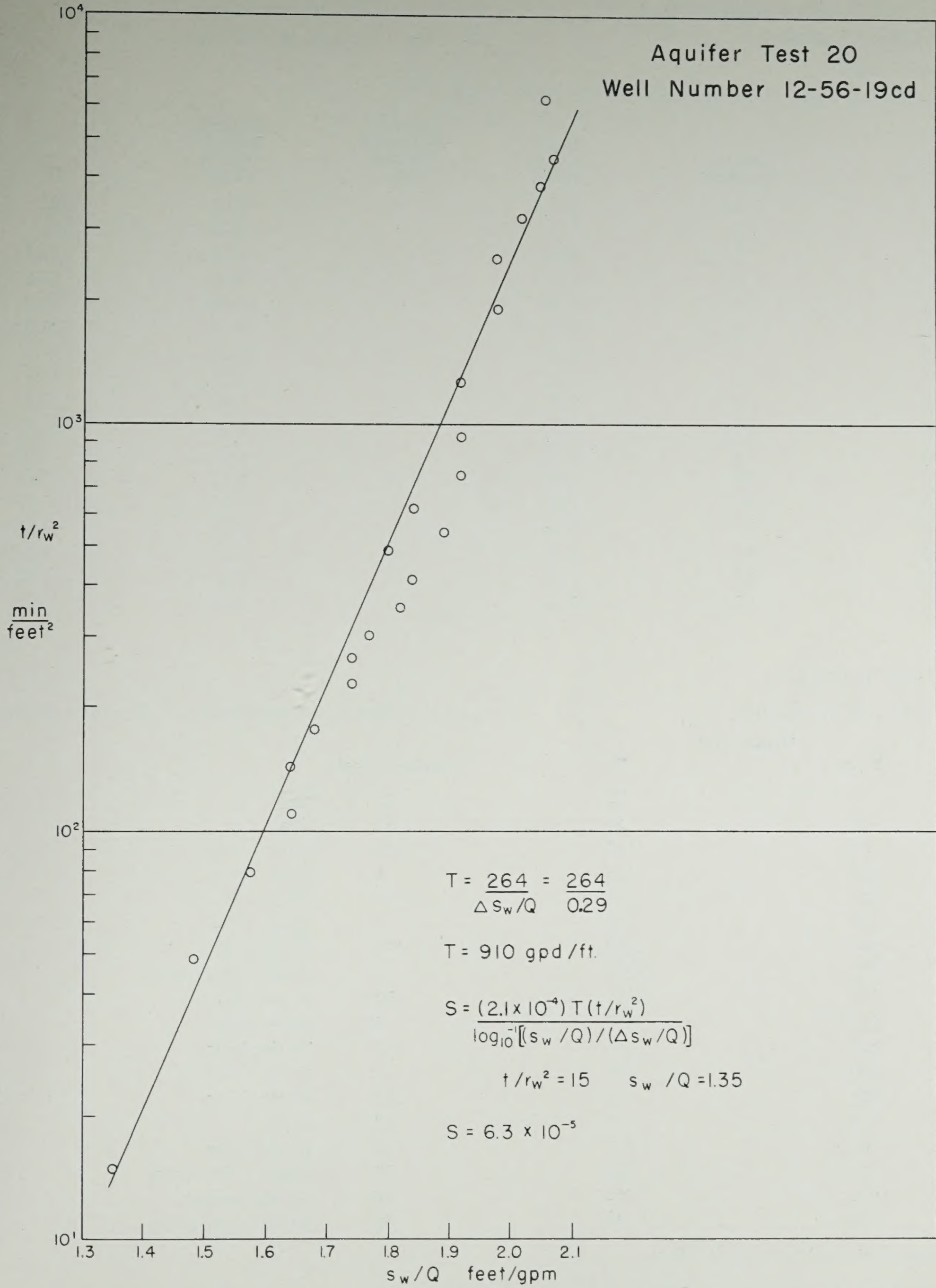
Test conducted by R. G. McMurtrey and O. James Taylor

Static head	9.72 feet of water
Reservoir depression	— .05 feet of water
Actual static head	9.67 feet of water

Flowing head	2.10 feet of water
Reservoir depression	—0.10 feet of water
Actual flowing head	2.00 feet of water

s_w = 9.67-2.00 = 7.67 feet of water
$r_w = 1.25 \times 10^{-1}$ ft. $(r_w)^2 = 1.56 \times 10^{-2}$ ft^2

Time t (min-sec)	Discharge Q (gpm)	s_w/Q (feet/gpm)	$t/(r_w)^2$ (min/ft^2)
00-14	5.69	1.35	15.0
00-46	5.18	1.48	49.0
01-14	4.87	1.575	79.0
01-43	4.66	1.64	110
02-15	4.66	1.64	144
02-47	4.57	1.68	178
03-38	4.41	1.74	232
04-10	4.41	1.74	266
04-45	4.34	1.77	304
05-30	4.21	1.82	353
06-35	4.16	1.84	420
07-40	4.28	1.80	490
08-25	4.05	1.89	539
09-40	4.15	1.84	619
11-48	3.99	1.92	752
14-32	3.99	1.92	930
20-00	3.99	1.92	1,280
29-55	3.89	1.98	1,920
40-00	3.87	1.98	2,560
50-00	3.81	2.02	3,200
60-00	3.75	2.05	3,840
70-00	3.69	2.07	4,480
98-00	3.73	2.06	6,260


Aquifer Test 20
Well Number 12-56-19cd
10^4
10^3
10^2
10^1
t/r_w^2
$\frac{min}{feet^2}$
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
2.1
s_w/Q feet/gpm
$T = \frac{264}{\Delta s_w/Q} = \frac{264}{0.29}$
T = 910 gpd/ft.
$S = \frac{(2.1 \times 10^{-4})\,T\,(t/r_w^2)}{\log_{10}^{-1}[(s_w/Q)/(\Delta s_w/Q)]}$
$t/r_w^2 = 15$ $s_w/Q = 1.35$
$S = 6.3 \times 10^{-5}$

Aquifer test 21 (Flow recovery test)
Well number 12-56-19cd
August 11, 1963
Test conducted by R. G. McMurtrey and O. James Taylor

Static head 9.67 feet of water
Average discharge, Q = 3.80 gpm

Time t (minutes)	Time t′ (minutes)	Head (feet of water)	Reservoir depression (feet of water)	Adjusted head h′ (feet of water)	t/t′
100.5	0.5	8.03	0	8.03	201
101	1	8.28		8.28	101
102	2	8.50		8.50	51.0
103	3	8.62	0	8.62	34.3
104	4	8.70		8.70	26.0
105	5	8.78		8.78	21.0
106	6	8.82	0	8.82	17.7
107	7	8.86		8.86	15.3
108	8	8.90	0	8.90	13.5
110	10	8.93		8.93	11.0
115	15	9.07		9.07	7.67
120	20	9.17	0	9.17	6.00
125	25	9.20		9.20	5.00
130	30	9.25		9.25	4.33
140	40	9.31	0	9.31	3.50
160	60	9.42		9.42	2.67
180	80	9.50	0	9.50	2.25

Log of well 12-56-19cd

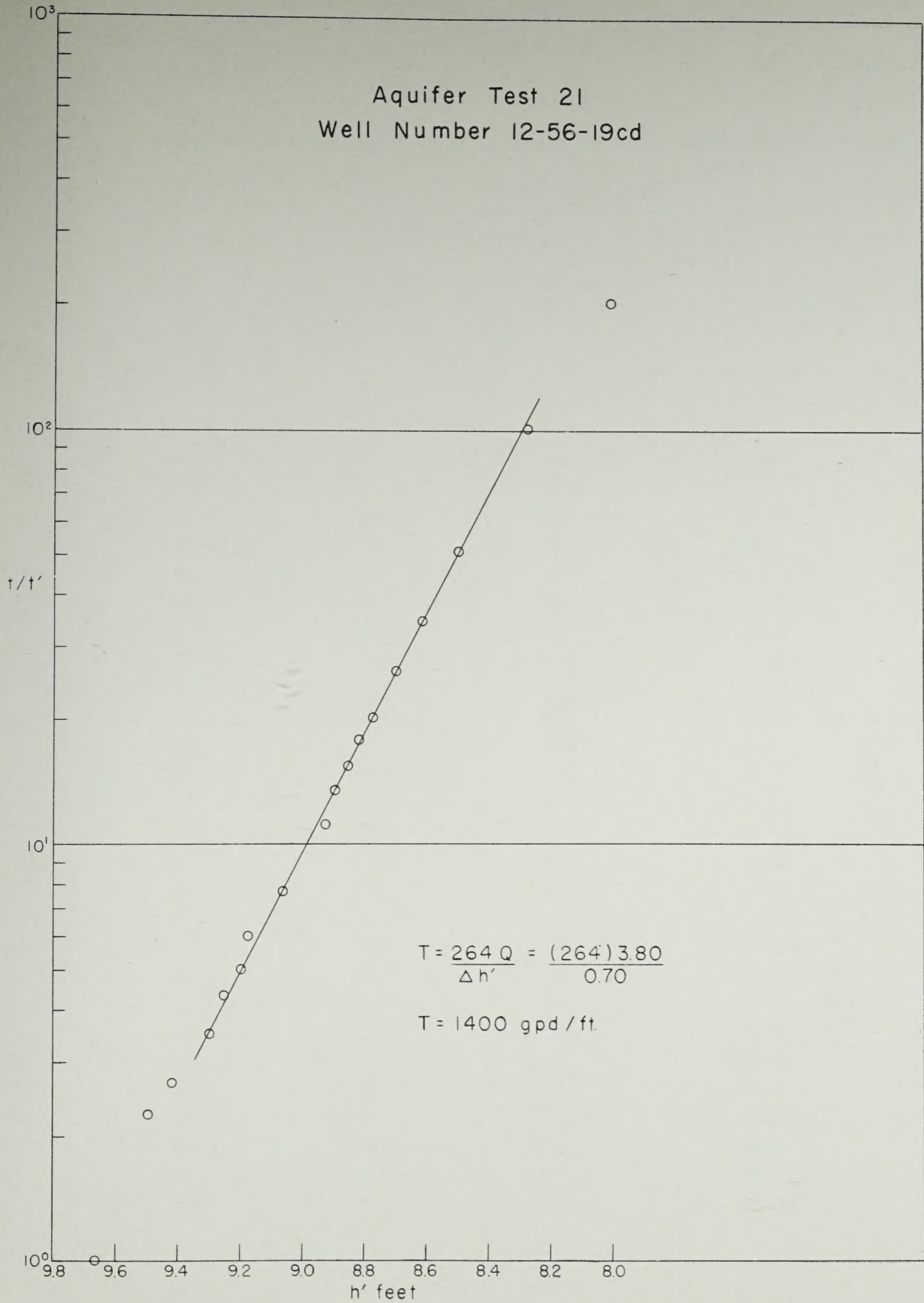
Well owner, D. H. Baggott

Log provided by Frank Bandy, Jr., Broadus, Montana

Depth (feet) From	To	Thickness (feet)	
0	25	25	Soil
25	37	12	Coal
37	143	106	Shale, blue
143	144	1	Rock, hard
144	271	127	Shale, blue
271	274	3	Rock, hard
274	400	126	Shale, blue
400	407	7	Sand, with water
407	457	50	Shale, blue
457	460	3	Rock, hard
460	665	205	Shale, blue
665	667	2	Rock, hard
667	776	109	Shale, blue
776	792	16	Sand
792	865	73	Shale, blue
865	920	55	Sand, with water
920	980	60	Shale, sandy
980	1,140	160	Sand, with water

Assumed aquifer thickness 268 feet.

Cased to 1,109 feet with 2-inch casing. Originally flowed 15 gpm.



Aquifer Test 21
Well Number 12-56-19cd
10^3
10^2
10^1
10^0
t/t′
T = 264 Q / Δh′ = (264) 3.80 / 0.70
T = 1400 gpd/ft.
9.8
9.6
9.4
9.2
9.0
8.8
8.6
8.4
8.2
8.0
h′ feet

Aquifer test 22 (Flow test)

Well number 12-55-16db

August 7, 1963

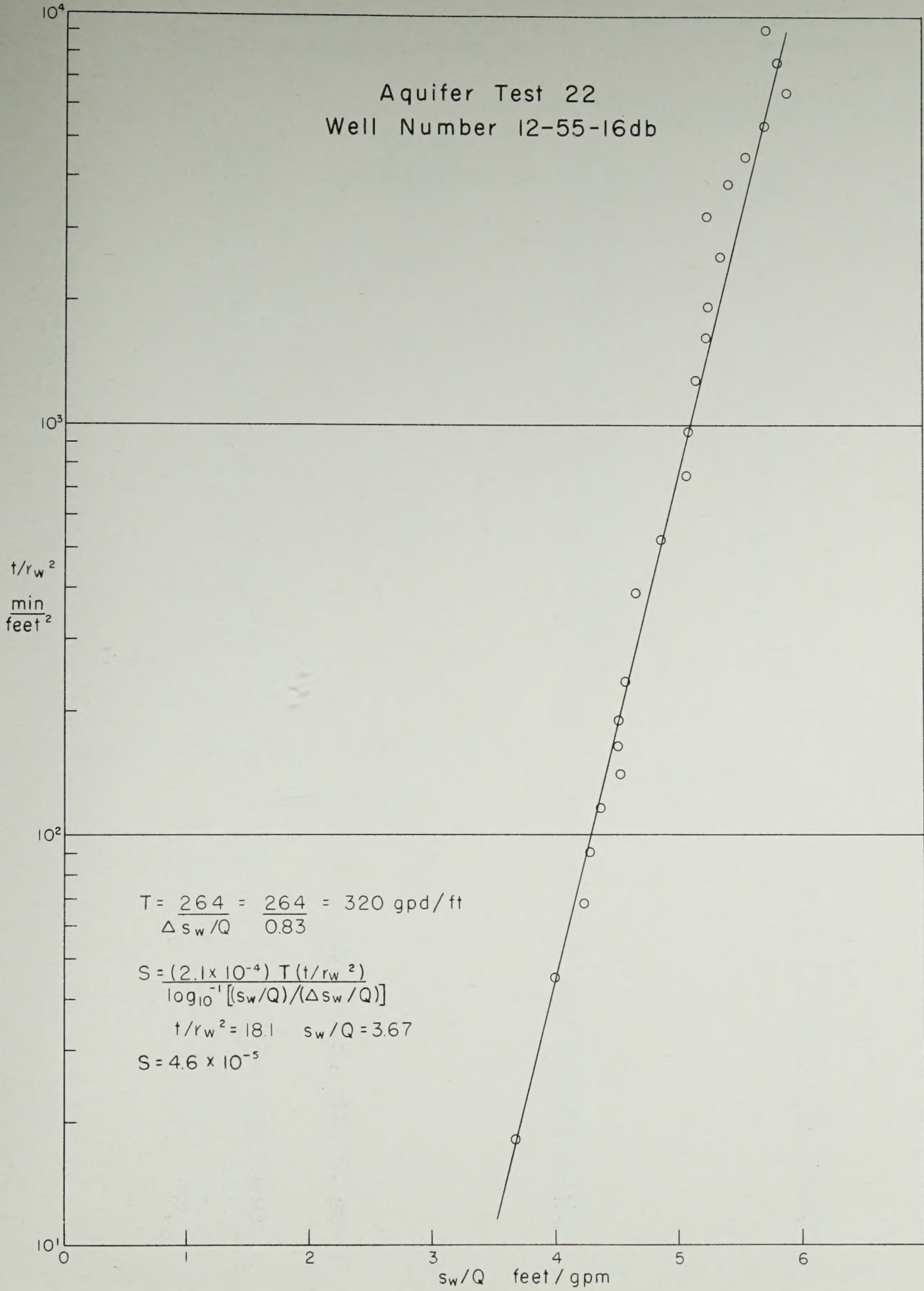
Test conducted by S. W. Lohman, Charles Lane, R. G. McMurtrey, and O. James Taylor

Static head	89.50 feet of water
Reservoir depression	+ 0.80 feet of water
Actual static head	90.30 feet of water

Flowing head	3.30 feet of water
Reservoir depression	+ 0.25 feet of water
Actual flowing head	3.55 feet of water

s_w = 90.30-3.55 = 86.75 feet of water.
$r_w = 1.25 \times 10^{-1} \times 10^{-1}$ ft. $(r_w)^2 = 1.56 \times 10^{-2}$ ft^2

Time t (min-sec)	Discharge Q (gpm)	s_w/Q (feet/gpm)	$t/(r_w)^2$ (min/ft^2)
00-17	23.6	3.67	18.1
00-42	21.7	4.00	44.8
01-04	20.5	4.23	68.2
01-25	20.3	4.28	90.6
01-50	19.9	4.36	117
02-11	19.2	4.51	140
02-33	19.2	4.51	163
02-56	19.2	4.51	188
03-43	19.0	4.56	238
06-02	18.6	4.66	386
08-50	17.85	4.86	522
11-45	17.1	5.08	750
15-00	17.0	5.10	960
20-07	16.85	5.14	1,290
25-05	16.6	5.21	1,605
30-10	16.5	5.25	1,930
40-07	16.2	5.35	2,565
50-15	16.5	5.25	3,210
50-50	16.5	5.25	3,250
60-04	16.0	5.41	3,840
70-25	15.6	5.55	4,500
84-18	15.2	5.71	5,390
102-00	14.7	5.90	6,520
120-00	14.9	5.81	7,670
143-45	15.1	5.72	9,200


Aquifer Test 22
Well Number 12-55-16db
$T = \frac{264}{\Delta s_w/Q} = \frac{264}{0.83} = 320$ gpd/ft
$S = \frac{(2.1 \times 10^{-4})\, T\, (t/r_w^2)}{\log_{10}^{-1}[(s_w/Q)/(\Delta s_w/Q)]}$
$t/r_w^2 = 18.1$ $s_w/Q = 3.67$
$S = 4.6 \times 10^{-5}$
t/r_w^2
$\frac{\text{min}}{\text{feet}^2}$
10^4
10^3
10^2
10^1
0
1
2
3
4
5
6
s_w/Q feet / gpm

Aquifer test 23 (Flow recovery test)
Well number 12-55-16db
August 7, 1963
Test conducted by S. W. Lohman, Charles Lane, R. G. McMurtrey, and O. James Taylor

Static head 90.30 feet of water
Average discharge, Q = 16.0 gpm

Time t (minutes)	Time t′ (minutes)	Head (feet of water)	Reservoir depression (feet of water)	Adjusted head h′ (feet of water)	t/t′
151	1	65.18	0.70	65.88	151.
152	2	68.72		69.45	76.0
153	3	70.71	.75	71.46	51.0
154	4	72.07		72.84	38.5
155	5	73.13		73.92	31.0
156	6	74.01	.80	74.81	26.0
158	8	75.40		76.20	19.8
160	10	76.47		77.27	16.0
163	13	77.70	.80	78.50	12.5
166	16	78.63		79.43	10.4
170	20	79.63		80.43	8.50
175	25	80.59		81.39	7.00
181	31	81.48	.80	82.28	5.84
185	35	81.95		82.75	5.14
190	40	82.49		83.29	4.75
195	45	82.93		83.73	4.33
200	50	83.32		84.12	4.00
220	70	84.56		85.36	3.14

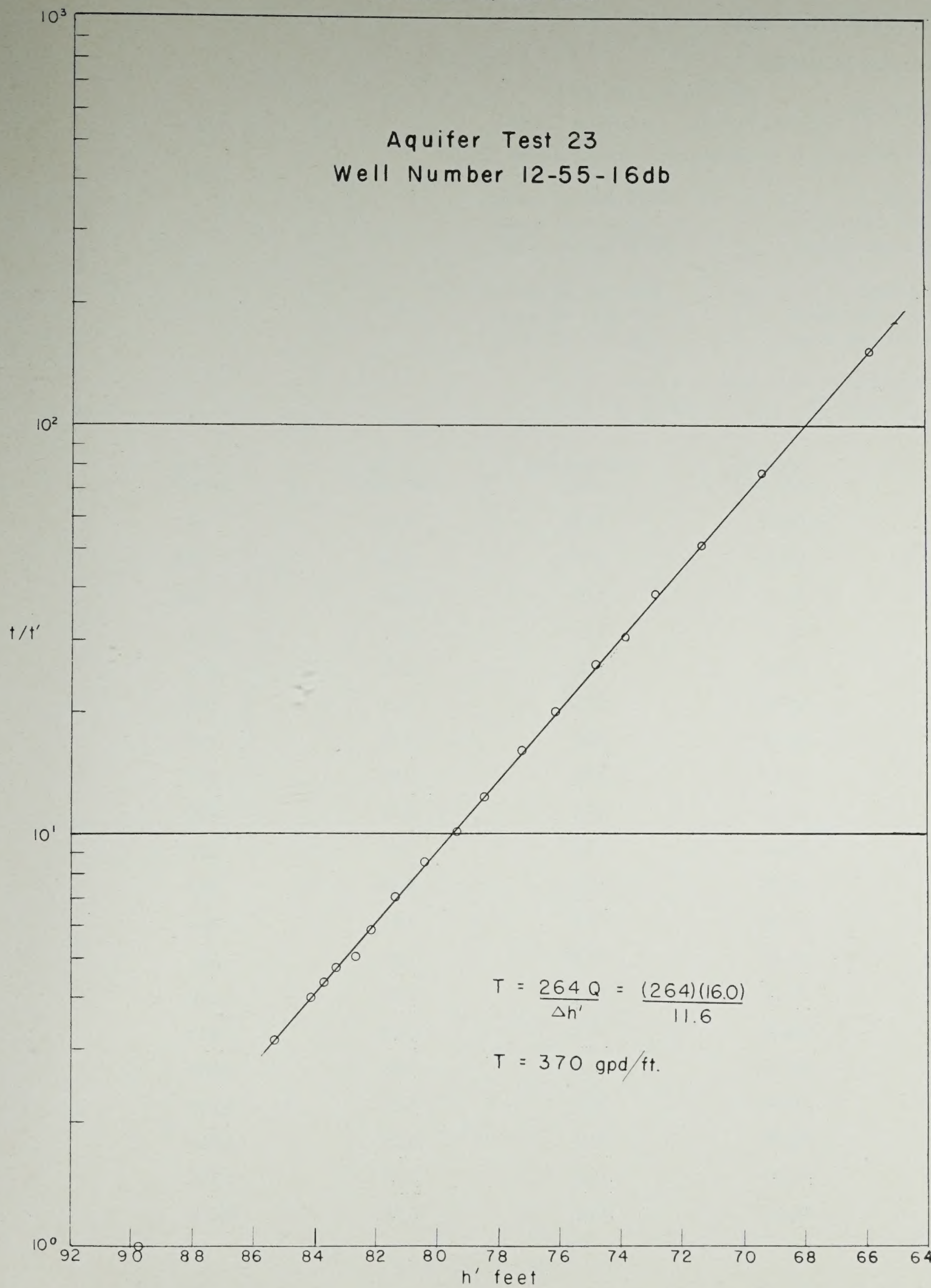
Log of well 12-55-16db
Well owner, Leo Lund

Log provided by Frank Bandy, Jr., Broadus, Montana

Depth (feet) From	To	Thickness (feet)	
0	16	16	Soil
16	94	78	Blue shale
94	97	3	Hard rock
97	103	6	Blue shale
103	106	3	Coal
106	283	177	Blue shale
283	304	21	Water sand
304	308	4	Hard rock
308	484	176	Blue shale
484	522	38	Water sand
522	545	23	Blue shale
545	548	3	Hard rock
548	564	16	Blue shale
564	568	4	Hard rock
568	703	135	Blue shale
703	741	38	Sand
741	752	11	Hard rock
752	830	78	Blue shale
830	920	90	Water sand

Cased with 900 feet of 2-inch pipe, seated at 540 feet.

Assumed aquifer thickness 128 feet.


Aquifer Test 23
Well Number 12-55-16db
$T = \frac{264\,Q}{\Delta h'} = \frac{(264)(16.0)}{11.6}$
T = 370 gpd/ft.
t/t'
h' feet
10^0
10^1
10^2
10^3
92
90
88
86
84
82
80
78
76
74
72
70
68
66
64

Aquifer test 24 (Flow test)

Well number 12-55-15bc

August 12, 1963

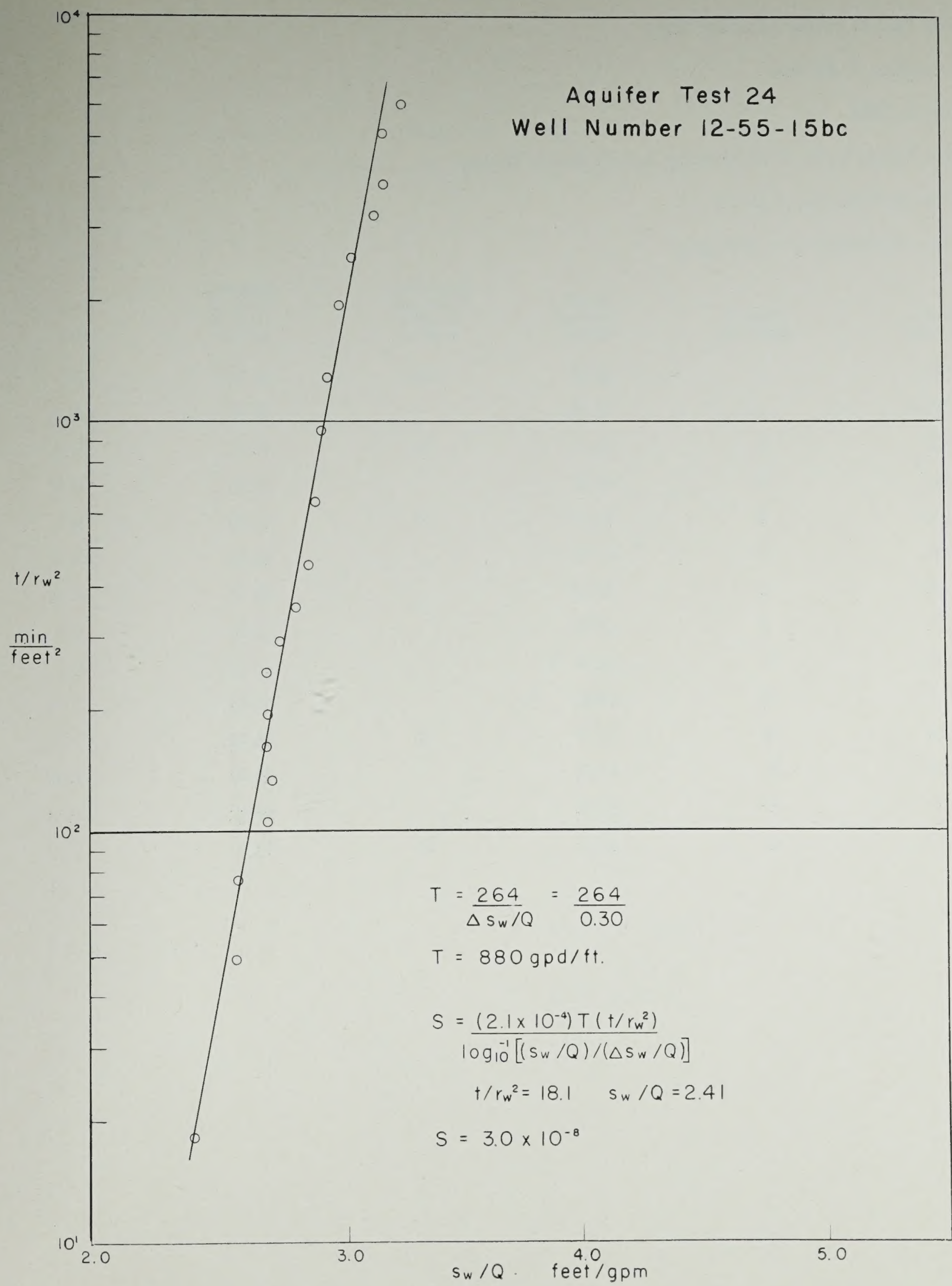
Test conducted by R. G. McMurtrey and O. James Taylor

Static head	48.36 feet of water
Reservoir depression	+ 0.30 feet of water
Actual static head	48.66 feet of water

Flowing head	2.65 feet of water
Reservoir depression	+ 0.00 feet of water
Actual flowing head	2.65 feet of water

s_W = 48.66-2.65 = 46.01 feet of water
$r_W = 1.25 \times 10^{-1}$ ft. $(r_W)^2 = 1.56 \times 10^{-2}$ ft^2

Time t (min-sec)	Discharge Q (gpm)	s_W/Q (feet/gpm)	$t/(r_W)^2$ (min/ft^2)
00-17	19.05	2.41	18.1
00-46	17.8	2.58	49.0
01-12	17.7	2.60	76.9
01-40	17.0	2.71	106
02-07	16.8	2.73	135
02-32	16.9	2.72	162
03-00	16.9	2.72	192
03-52	17.0	2.71	247
04-35	16.6	2.77	294
05-33	16.2	2.84	355
06-55	15.9	2.89	449
10-00	15.8	2.91	640
15-00	15.65	2.94	960
20-00	15.45	2.97	1,280
30-00	15.2	3.02	1,920
40-00	15.0	3.06	2,560
50-00	14.5	3.17	3,200
60-00	14.4	3.20	3,840
80-00	14.4	3.20	5,120
95-00	14.0	3.28	6,080


Aquifer Test 24
Well Number 12-55-15bc
$T = \frac{264}{\Delta s_w/Q} = \frac{264}{0.30}$
T = 880 gpd/ft.
$S = \frac{(2.1 \times 10^{-4})\, T\, (t/r_w^2)}{\log_{10}^{-1}\left[(s_w/Q)/(\Delta s_w/Q)\right]}$
$t/r_w^2 = 18.1$ $s_w/Q = 2.41$
$S = 3.0 \times 10^{-8}$
t/r_w^2
$\frac{\text{min}}{\text{feet}^2}$
10^4
10^3
10^2
10^1
2.0
3.0
4.0
5.0
s_w/Q · feet/gpm

Aquifer test 25 (Flow recovery test)

Well number 12-55-15bc

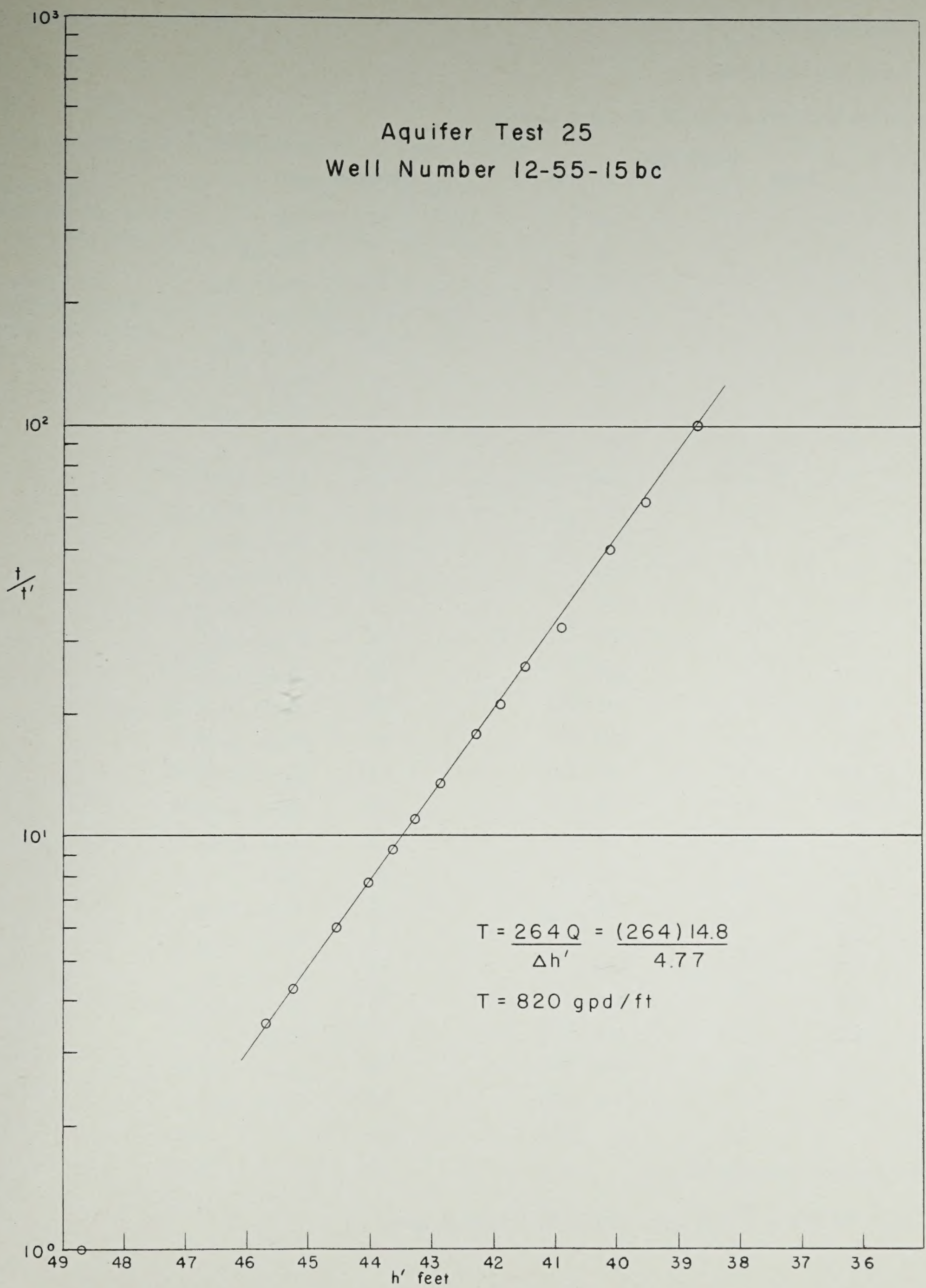
August 12, 1963

Test conducted by R. G. McMurtrey and O. James Taylor

Static head 48.66 feet of water

Average discharge, Q = 14.8 gpm

Time t (minutes)	Time t′ (minutes)	Head (feet of water)	Reservoir depression (feet of water)	Adjusted head h′ (feet of water)	t/t′
101	1	38.45	0.25	38.70	101
101.5	1.5	39.30		39.55	67.7
102	2	39.87	.25	40.12	51.0
103	3	40.68		40.93	34.3
104	4	41.27	.25	41.52	26.0
105	5	41.72		41.96	21.0
106	6	42.07		42.32	17.7
108	8	42.64		42.89	13.5
110	10	43.05		43.30	11.0
112	12	43.40		43.65	9.30
115	15	43.84	.25	44.09	7.70
120	20	44.34		44.59	6.00
130	30	45.05		45.30	4.33
140	40	45.52	.25	45.77	3.50


Aquifer Test 25
Well Number 12-55-15bc
$T = \frac{264Q}{\Delta h'} = \frac{(264)\,14.8}{4.77}$
T = 820 gpd/ft
10^3
10^2
10^1
10^0
t/t'
49 48 47 46 45 44 43 42 41 40 39 38 37 36
h' feet

Log of well 12-55-15bc

Well owner, Mr. Leo Lund

Log provided by Frank Bandy, Jr., Broadus, Montana

Depth (feet) From	To	Thickness (feet)	
0	16	16	Soil
16	23	7	Gravel
23	51	28	Shale, blue
51	57	6	Coal
57	121	64	Shale, blue
121	132	11	Sand
132	143	11	Shale, blue
143	147	4	Sand
147	156	9	Rock, hard
156	248	92	Shale, blue
248	251	3	Rock, hard
251	467	216	Shale, blue
467	535	68	Shale, sandy and coal
535	537	2	Rock, hard
537	566	29	Shale, sandy
566	611	45	Shale, blue and sand
611	678	67	Shale, sandy
678	683	5	Rock, hard
683	735	52	Shale, blue
735	740	5	Rock, hard
740	768	28	Sand
768	806	38	Shale, blue
806	808	2	Rock, hard
808	882	74	Shale, blue
882	907	25	Sand, with water
907	912	5	Rock, hard
912	960	48	Sand, with water
960	980	20	Shale, blue

Assumed aquifer thickness 222 feet.

Cased with 924 feet of 2-inch pipe. Originally flowed 25 gpm.

Aquifer test 26 (Flow test)

Well number 12-55-8cc

August 12, 1963

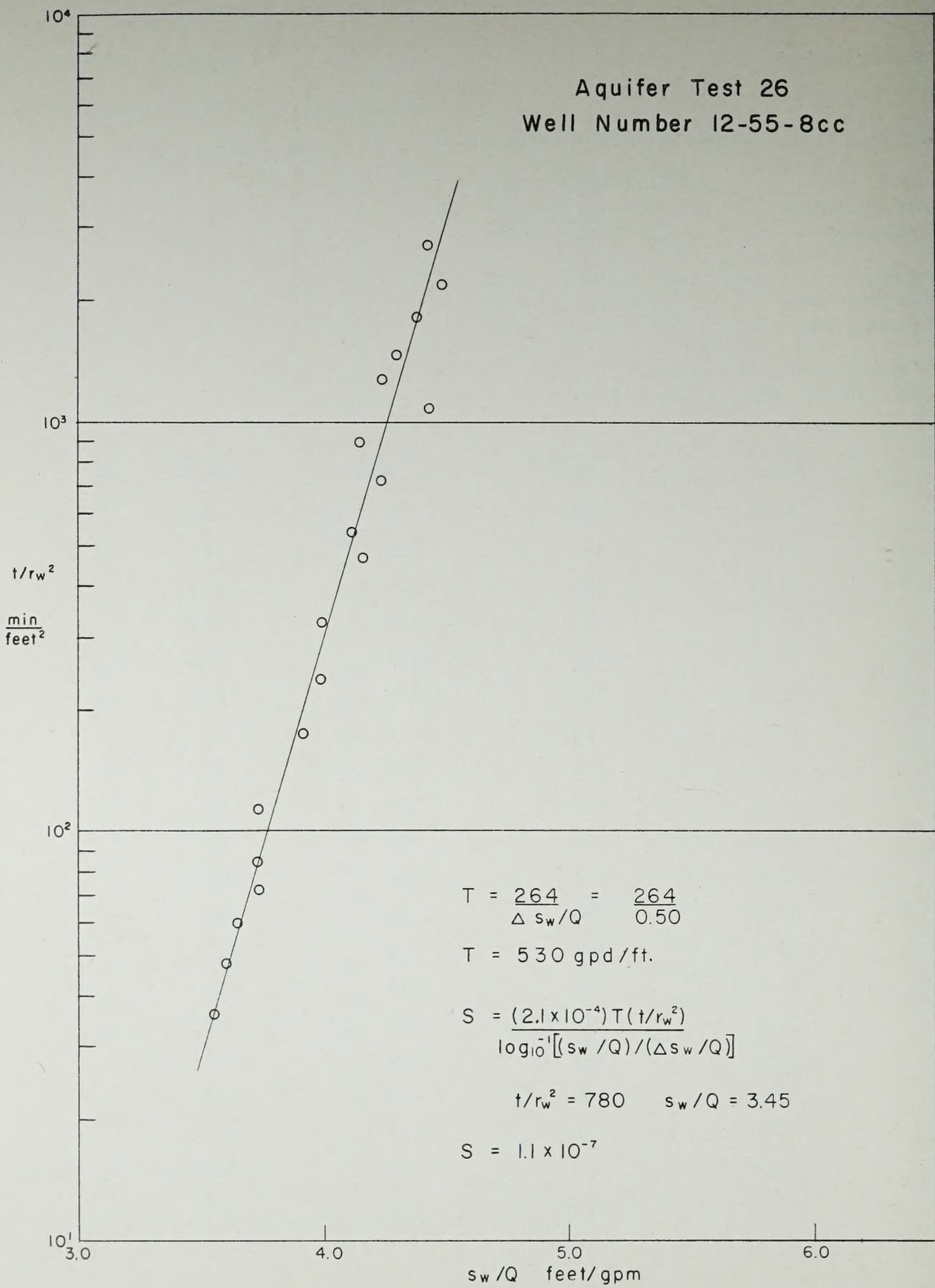
Test conducted by R. G. McMurtrey and O. James Taylor

Static head	71.22 feet of water
Reservoir depression	+ 0.45 feet of water
Actual static head	71.67 feet of water

Flowing head	1.75 feet of water
Reservoir depression	+ 0.00 feet of water
Actual flowing head	1.75 feet of water

s_w = 71.67-1.75 = 69.92 feet of water
$r_w = 1.66 \times 10^{-1}$ ft. $(r_w)^2 = 2.78 \times 10^{-2}$ ft^2

Time t (min-sec)	Discharge Q (gpm)	s_w/Q (feet/gpm)	$t/(r_w)^2$ (min/ft^2)
00-13	20.25	3.45	7.80
01-00	19.7	3.55	36.0
01-20	19.4	3.60	48.0
01-40	19.2	3.64	60.0
02-00	18.7	3.73	72.0
02-22	18.7	3.73	85.0
03-11	18.7	3.73	115
04-47	17.8	3.92	172
06-37	17.5	3.99	238
09-00	17.5	3.99	324
13-00	16.8	4.16	468
15-00	16.9	4.12	540
20-00	16.5	4.24	720
25-00	16.9	4.15	900
30-00	15.8	4.43	1,080
35-00	16.5	4.24	1,260
40-00	16.4	4.29	1,440
50-00	16.0	4.38	1,800
60-00	15.6	4.49	2,160
75-00	15.8	4.43	2,700


Aquifer Test 26
Well Number 12-55-8cc
10^4
10^3
10^2
10^1
t/r_w^2
$\frac{\text{min}}{\text{feet}^2}$
$T = \frac{264}{\Delta s_w/Q} = \frac{264}{0.50}$
$T = 530$ gpd/ft.
$S = \frac{(2.1 \times 10^{-4})T(t/r_w^2)}{\log_{10}^{-1}[(s_w/Q)/(\Delta s_w/Q)]}$
$t/r_w^2 = 780 \quad s_w/Q = 3.45$
$S = 1.1 \times 10^{-7}$
3.0
4.0
5.0
6.0
s_w/Q feet/gpm

Aquifer test 27 (Flow recovery test)

Well number 12-55-8cc

August 12, 1963

Test conducted by R. G. McMurtrey and O. James Taylor

Static head 71.67 feet of water

Average discharge, Q = 16.3 gpm

Time t (minutes)	Time t′ (minutes)	Head (feet of water)	Reservoir depression (feet of water)	Adjusted head h′ (feet of water)	t/t′
81	1	56.80	0.35	57.15	81.0
81.5	1.5	58.26		58.61	54.3
82	2	59.36		59.71	41.0
83	3	60.78	.35	61.13	27.7
84	4	61.69		62.04	21.0
86	6	62.80		63.15	14.3
115	35	67.42	.40	67.82	3.30
120	40	67.76		68.16	3.00
130	50	68.16		68.56	2.60
140	60	68.53	.40	68.93	2.33

Log of well 12-55-8cc

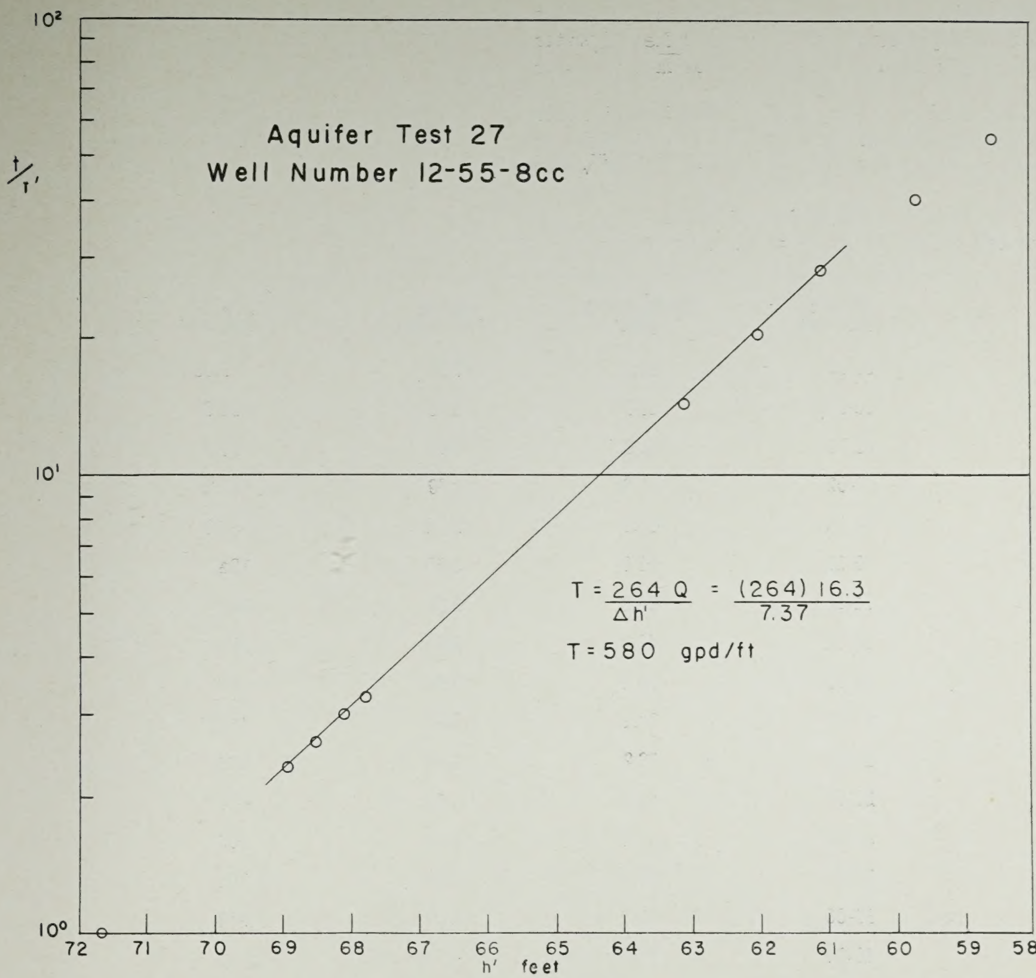
Log provided by Mr. Ira C. Bond, Terry, Montana

Well owner, Mr. J. D. Strobel

Depth (feet) From	To	Thickness (feet)	
0	3	3	Gumbo
3	12	9	Sand
12	28	16	Clay, sandy
28	65	37	Clay, blue
65	68	3	Coal
68	102	34	Gumbo, gray
102	106	4	Coal
106	122	16	Gumbo, brown
122	125	3	Coal
125	147	22	Gumbo
147	148	1	Rock
148	158	10	Gumbo
158	159	1	Coal
159	160	1	Coal
160	177	17	Coal
177	180	3	Coal
180	185	5	Gumbo
185	187	2	Rock, hard
187	188	1	Coal
188	190	2	Gumbo
190	198	8	Gumbo and coal
198	199	1	Rock
199	217	18	Gumbo
217	219	2	Rock
219	246	27	Coal and gumbo
246	249	3	Rock, hard
249	267	18	Gumbo
267	270	3	Coal and gumbo
270	280	10	Gumbo
280	330	50	Gumbo and sand
330	331	1	Rock
331	340	9	Gumbo
340	360	20	Gumbo and coal
360	380	20	Gumbo, sandy and coal
380	382	2	Coal
382	417	35	Gumbo, sandy
417	418	1	Rock, hard
418	457	39	Gumbo
457	460	3	Coal
460	493	33	Gumbo
493	494	1	Rock
494	606	112	Shale
606	608	2	Rock
608	660	52	Shale
660	661	1	Rock
661	722	61	Shale
722	724	2	Rock
724	840	116	Shale
840	842	2	Rock
842	869	27	Shale
869	929	60	Sand, with 25 gpm flow
929	960	31	Shale

Assumed aquifer thickness 60 feet.

Casing perforated 869-929 feet.


Aquifer Test 27
Well Number 12-55-8cc
10^2
10^1
10^0
t/t'
T = 264 Q / Δh' = (264) 16.3 / 7.37
T = 580 gpd/ft
72 71 70 69 68 67 66 65 64 63 62 61 60 59 58
h' feet

Aquifer test 28 (Flow test)

Well number 13-54-22ca

August 10, 1963

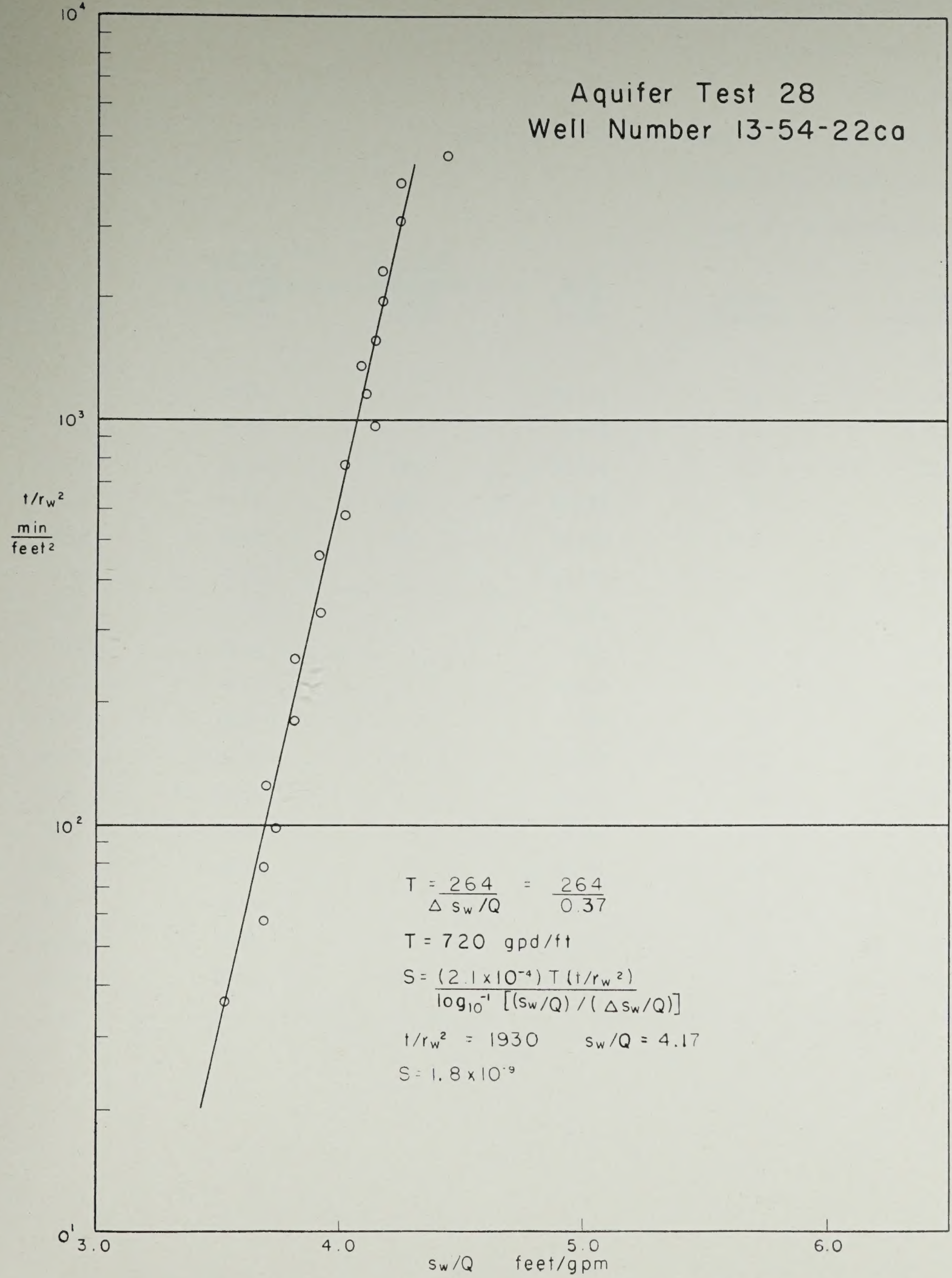
Test conducted by R. G. McMurtrey and O. James Taylor

Static head	155.20 feet of water
Reservoir depression	+ 0.70 feet of water
Actual static head	155.90 feet of water

Flowing head	2.54 feet of water
Reservoir depression	— 0.10 feet of water
Actual flowing head	2.44 feet of water

s_w = 155.90-2.44 = 153.46 feet of water.
$r_w = 1.61 \times 10^{-1}$ ft. $(r_w)^2 = 2.6 \times 10^{-2}$ ft^2

Time t (min-sec)	Discharge Q (gpm)	s_w/Q (feet/gpm)	$t/(r_w)^2$ (min/ft^2)
00-15	46.6	3.29	9.63
00-57	43.5	3.53	36.6
01-30	41.6	3.69	57.9
02-02	41.6	3.69	78.2
02-32	41.0	3.74	97.3
03-13	41.6	3.69	124
04-40	40.2	3.81	180
06-34	40.2	3.81	253
08-33	39.1	3.92	330
11-55	39.1	3.92	461
15-00	38.2	4.02	578
20-00	38.2	4.02	770
25-00	37.2	4.14	960
30-00	37.5	4.10	1,160
35-00	37.7	4.08	1,350
40-00	37.2	4.14	1,540
50-00	36.9	4.17	1,930
60-00	36.9	4.17	2,310
80-00	36.1	4.25	3,080
100-00	36.1	4.25	3,850
115-00	34.6	4.44	4,430


Aquifer Test 28
Well Number 13-54-22ca
10^4
10^3
10^2
10^1
t/r_w^2 $\frac{\text{min}}{\text{feet}^2}$
$T = \frac{264}{\Delta s_w/Q} = \frac{264}{0.37}$
T = 720 gpd/ft
$S = \frac{(2.1 \times 10^{-4})\, T\, (t/r_w^2)}{\log_{10}^{-1}\left[(s_w/Q)/(\Delta s_w/Q)\right]}$
$t/r_w^2 = 1930$ $s_w/Q = 4.17$
$S = 1.8 \times 10^{-9}$
3.0
4.0
5.0
6.0
s_w/Q feet/gpm

Aquifer test 29 (Flow recovery test)

Well number 13-54-22ca

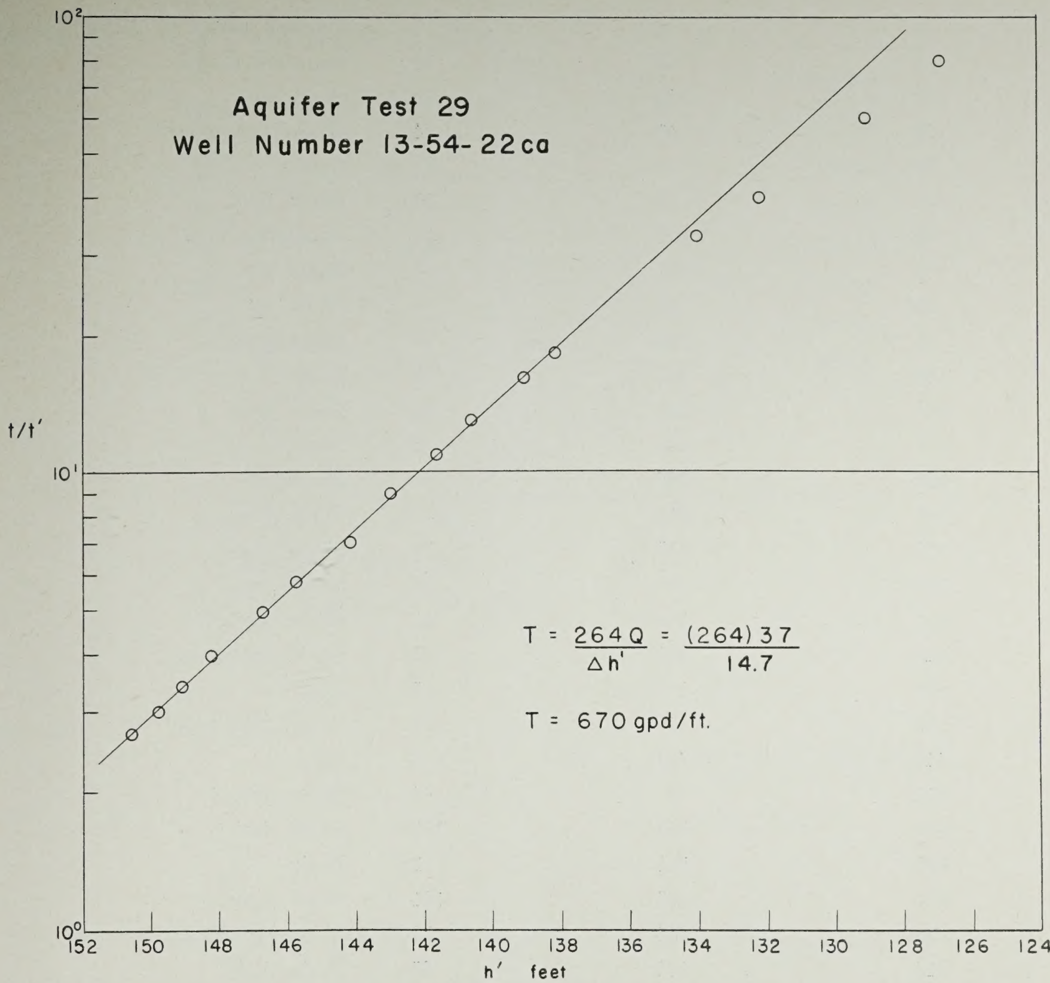
August 10, 1963

Test conducted by R. G. McMurtrey and O. James Taylor

Static head 155.90 feet of water

Average discharge, Q = 37 gpm

Time t (minutes)	Time t′ (minutes)	Head (feet of water)	Reservoir depression (feet of water)	Adjusted head h′ (feet of water)	t/t′
120	0				
121	1	123.20		123.85	121
121.5	1.5	126.25		126.90	81.0
122	2	128.44	0.65	129.09	61.0
123	3	131.50	.70	132.20	41.0
123.75	3.75	133.30	.75	134.05	33.0
127	7	137.47	.75	138.22	18.1
128	8	138.35		139.11	16.0
130	10	139.91		140.67	13.0
132	12	140.89		141.66	11.0
135	15	142.21		142.98	9.00
140	20	143.41	.78	144.19	7.00
145	25	145.05		145.83	5.80
150	30	146.00		146.78	5.00
160	40	147.45		148.23	4.00
170	50	148.35		149.13	3.40
180	60	149.10		149.88	3.00
190	70	149.82	.78	150.60	2.71


Aquifer Test 29
Well Number 13-54-22ca
$T = \frac{264\,Q}{\Delta h'} = \frac{(264)\,37}{14.7}$
T = 670 gpd/ft.
t/t'
10^2
10^1
10^0
152
150
148
146
144
142
140
138
136
134
132
130
128
126
124
h' feet

Log of well 13-54-22ca

Well owner, F. J. Haidle

Log provided by Henry Johnson, Terry, Montana

Depth (feet) From	To	Thickness (feet)	
0	5	5	Top soil, sandy
5	18	13	Sand and gravel
18	38	20	Sand, blue
38	42	4	Shale, light-blue
42	44	2	Coal
44	65	21	Shale, blue
65	78	13	Sandstone, blue
78	87	9	Shale, blue
87	89	2	Rock
89	185	96	Shale, gray
185	190	5	Coal
190	230	40	Shale, gray
230	235	5	Rock
235	247	12	Sandstone
247	270	23	Shale, green
270	285	15	Shale, gray
285	315	30	Sandstone
315	345	30	Shale, dark
345	370	25	Shale, light-gray
370	375	5	Coal
375	440	65	Shale, light-gray
440	441	1	Rock
441	487	46	Shale, gray
487	590	103	Shale, dark
590	591	1	Rock
591	695	104	Shale, gray
695	715	20	Shale, light-gray
715	750	35	Shale, dark
750	840	90	Shale, gray
840	855	15	Shale, brown
855	870	15	Shale, gray
870	915	45	Sandstone, gray with water

Assumed aquifer thickness 87 feet

Casing perforated 860-915 feet. Packer set at 165 feet.

Aquifer test 30 (Flow recovery test)

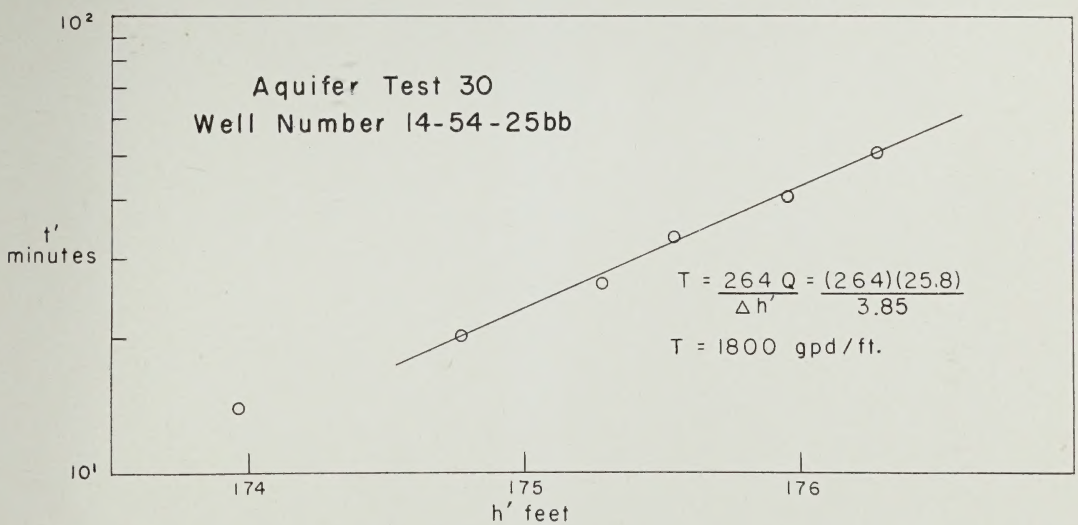
Well number 14-54-25bb

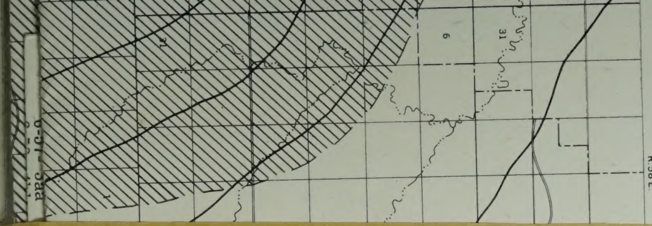
Agust 11, 1963

Test conducted by R. G. McMurtrey and O. James Taylor

Average discharge, Q = 25.8 gpm (t = very large)

Time t′ (minutes)	Head (feet of water)	Reservoir depression (feet of water)	Adjusted head h′ (feet of water)
14	173.16	0.80	173.96
20	173.97	.80	174.77
26	174.48	.80	175.28
33	174.75	.80	175.55
40	175.16	.80	175.96
50	175.48	.80	176.28





#4011031

Lobo - 250
Tollock 250
Hell Cr. 500
Fox Hills 150
1150

(6 enclosures)

TABLE 1.—RECORDS OF WELLS ALONG CEDAR CREEK ANTICLINE, MONTANA

Well number: The well numbering system used is explained in the text of this report.

Topographic location: C, creek bank; L, level or nearly so; U, undulating topography.

Type of well: Dr, drilled well; Du, dug well; Sp, spring.

Depth of well: Reported depths below the land surface are given in feet; measured depths are given in feet and tenths below measuring points.

Type of casing: C, concrete (brick tile or pipe); P, iron or steel pipe.

Character of material: Ss, sandstone.

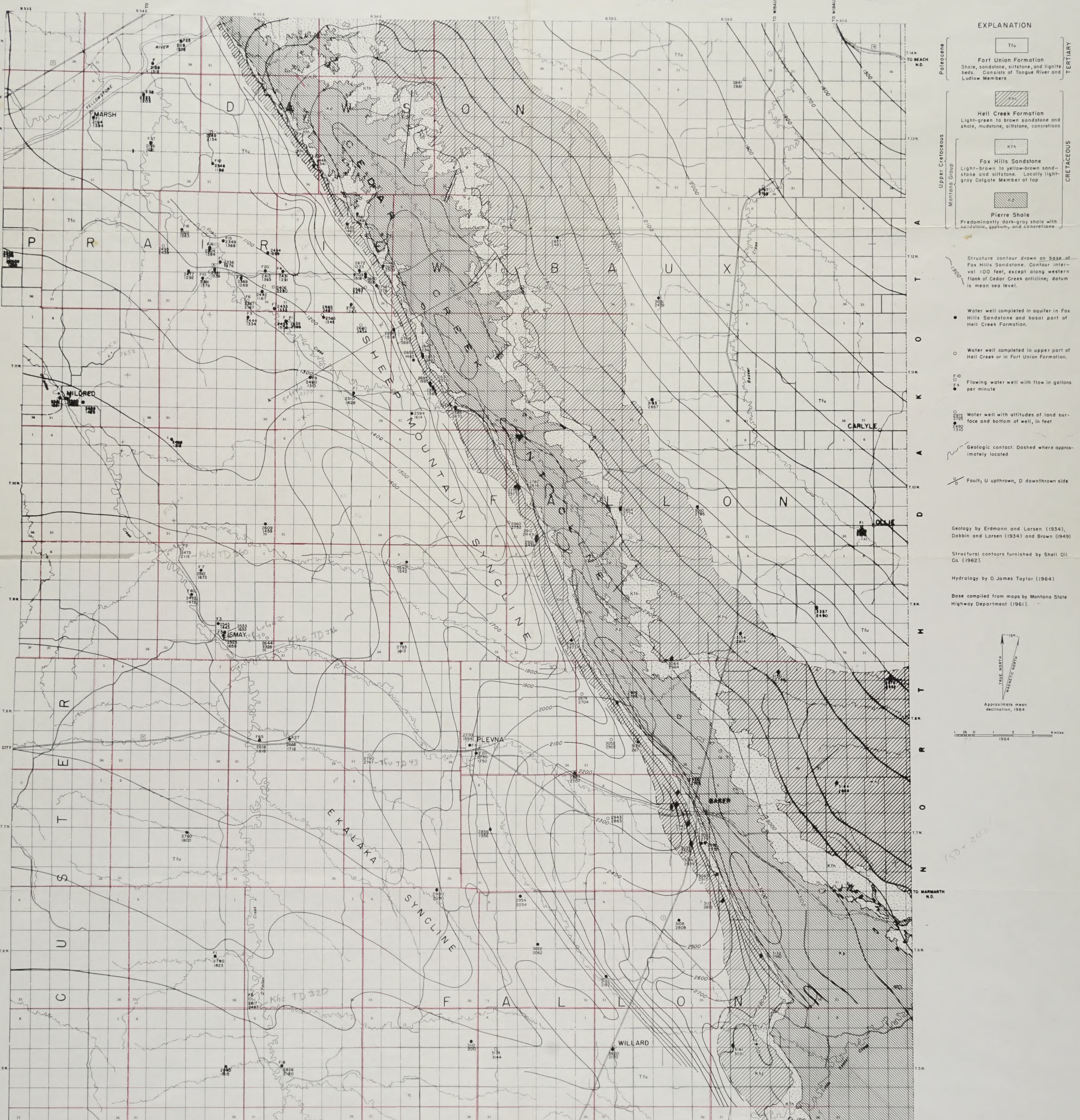
Geologic source: Kfh, Fox Hills Sandstone; Khc, Hell Creek Formation; Tfu, Fort Union Formation.

Method of lift: C, horizontal centrifugal; CY, cylinder; F, natural flow; N, none; S, submersible turbine; T, turbine.

Use of water: D, domestic; I, irrigation; In, industrial; N, not being used; P, public supply; S, stock.

Water level in relation to land surface: Measured depths to water level are given in feet, tenths and hundredths; reported depths to water level are given in feet. Heads above land surface are preceded by (+) and are given in feet, tenths, and hundredths.

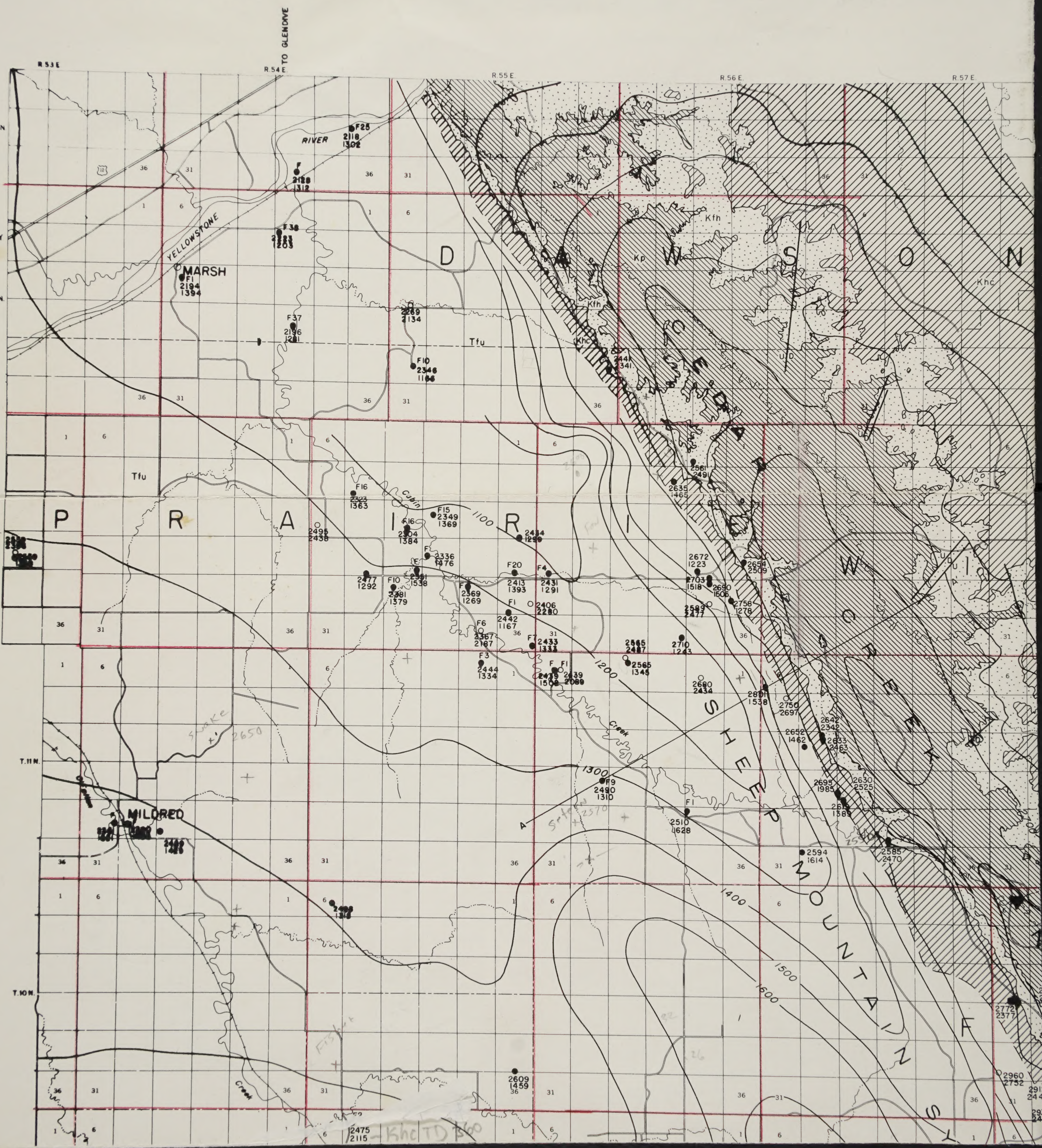
Well No.	Owner or Tenant	Year drilled	Topographic location	Type of well	Depth of well (feet)	Diameter of well (inches)	Type of Casing	Principal water-bearing bed: Character of material	Principal water-bearing bed: Geologic source	Method of lift	Use of water	Altitude of land surface (feet)	Water level in relation to land surface	Date of measurement	Remarks
							Western Flank								
5-15-13cc	Mackay Ranch		C	Dr	1,080	4	P	Ss	Kfh, Khc	CY	S	2,895	35	6-26-63	
5-56-17dd	Palm Ranch	1942	C	Dr	646	2	P	Ss	- - do - -	F	S	2,826	+47.25	7-16-63	18 gpm flow
5-57-12db	J. Ehret		U	Dr	1,100	1½	P	Ss	- - do - -	S	N	3,110	23.62	6-26-63	
5-58-18aa	Unknown		L	Dr	30	5	P		Tfu	CY	N	3,174	21.37	9- 4-63	
5-59-18aa	H. Hanson	1959	L	Dr	1,170		P	Ss	Kfh, Khc	S	D	3,300			
5-60- 8cc	T. Bechtold	1950	L	Dr	110	4	P	Ss	- - do - -	S	D	3,161	34.20	10- 1-62	
6-55-23ba	Mackay Ranch		C	Dr	967			Ss	- - do - -	F	S	2,790		6-26-63	Barely flows
6-56-31bc	- - - - do - - - -		L	Dr	320	2	P		Khc	F	S	2,817		9- 4-63	5 gpm flow
6-57- 3aa	E. Herbst	1957	L	Dr	810	4-2½	P	Ss	Kfh, Khc	S	D	2,900	21	1957	
6-58- 4bb	M. F. Allerdings	1948	L	Dr	900	4	P	Ss	- - do - -	S	D, S	2,954	35	1955	
6-58-15cc	- - - - do - - - -		C	Dr	960	4	P	Ss	- - do - -	CY	S	3,022	82.87	5- 5-64	
6-59-11bd	E. Fried		L	Dr	300	4	P	Ss	- - do - -	S	S	3,108	112.4	10- 2-62	
6-59-30ac	C. Barkley		C	Dr	920		P	Ss	- - do - -	S	D	3,102	106	1963	
6-60- 6ac	J. Singer		L	Dr	240	4	P	Ss	- - do - -	CY	N	3,112	119.3	9- 4-63	
6-60-21ac	A. Pinnow		U	Dr	150	4	P	Ss	- - do - -	S	D	3,132	110.70	10- 1-62	
7-55-22aa	Ron Perrin	1958	C	Dr	960	4	P	Ss	- - do - -	S	D, S	2,760	40	1963	
7-58-18dd	E. Huber	1958	U	Dr	900	4	P	Ss	- - do - -	C	D, S	2,856	10	5- 5-64	
7-59- 2cd	H. Beckman		L	Du	27	30	P	Ss	- - do - -	N	S	2,956	22.74	10-11-62	
7-59-11ca	City of Baker		L	Dr	500+	15	P	Ss	- - do - -	N	N	2,935	66.75	11-21-62	Pumping nearby
7-59-14da	- - - - do - - - -	1962	L	Dr	800	10¾	P	Ss	- - do - -	T	P	2,947	72.99	7-12-63	
7-59-18aa	R. Larson		U	Dr	80	5	P		Tfu	S	D	2,943	51.5	10- 2-62	
7-59-24db	G. Gunderson		L	Dr	225	8	P	Ss	Kfh	CY	I	3,022	92.5	10-11-62	
7-59-24da	- - - - do - - - -		L	Dr	60	6	P	Ss	- - do - -	N	N	2,992	48.66	10-11-62	
7-59-24cb	M. Gunderson		L	Dr	531		P	Ss	Kfh, Khc	S	D	3,039	87.24	10- 2-62	
7-59-25bb	- - - - do - - - -		U	Dr	75	4	P		Khc	CY	S	3,014	61.76	10- 2-62	
7-60-31ba	W. Singer		L	Dr	150		P	Ss	Kfh	CY	D, S	3,065	82.16	9- 4-63	
8-56-27bc	Reiger Brothers	1959	L	Dr	948	2	P	Ss	Kfh, Khc	F	S	2,666	+28.61	8- 9-63	27 gpm flow
8-56-29ac	- - - - do - - - -	1930	L	Dr	1,000	4-2	P	Ss	- - do - -	F	D, S, I	2,618		8-30-63	65 gpm flow
8-57-32ba	E. Herbst		L		43				Tfu	CY	N	2,790	38.95	10-11-62	
8-58-30dd	City of Plevna		C	Dr	1,000	8	P	Ss	Kfh, Khc	F	P	2,750	+34.35	6-28-63	20 gpm flow
8-58-30bd	- - - - do - - - -		L	Dr	1,176	6	P	Ss	- - do - -	S, F	P	2,770		6-27-63	1 gpm flow
8-58-36dd	G. J. Meyer		L	Dr	730	4	P	Ss	- - do - -	C	D	2,887	21.97	10- 3-62	
8-59- 7cd	W. Geving		L	Dr	170	4	P		Khc	CY	S	2,874	16.45	10- 3-62	
8-59-16bc	Rush Hall	1961	L	Dr	250	4	P	Ss	Kfh	CY	S	2,975	77.38	10- 2-63	
8-59-27bd	Montana-Dakota Utilities Co.		L	Dr	455		P	Ss	Kfh, Khc	CY	N	3,126	203.41	7-25-63	
8-59-29aa	B. J. Sinclair		U	Dr	150	4	P		Tfu	C	D	3,052	88.4	10- 3-62	
9-55- 5bc	Bill Almy		L	Dr	360	2	P		Khc	F	S	2,475		7- 1-63	2 gpm flow
9-55- 9bd	C. Shumaker	1958	U	Dr	837	2	P	Ss	Kfh, Khc	F	S	2,510	+14.30	7-15-63	7 gpm flow
9-55-17db	- - - - do - - - -	1935	C	Dr	1,000	6	P	Ss	- - do - -	F	D, S	2,472		7- 1-63	40 gpm flow
9-55-25dc	Ed May		U	Dr	316	4	P		Khc	C	S	2,644	42.9	10- 4-62	
9-55-27cal	G. Askin		L	Dr	865	2	P	Ss	Kfh, Khc	F	D	2,523			
9-55-27ca2	E. Hoem		L	Dr	900	2	P	Ss	- - do - -	F	D	2,533		7-15-63	5 gpm flow
9-55-27bb	Bill Almy		L	Dr	1,100	2	P	Ss	- - do - -	F	S	2,543	+12.60	7- 3-63	3 gpm flow
9-57- 6dd	E. Heuer		L	Dr	1,150	4	P	Ss	- - do - -	CY	N	2,692	19.96	10- 2-63	
9-57-31ab	A. Berkle	1949	L	Dr	980	4	P	Ss	- - do - -	S	D, S	2,793	88.93	7-24-62	
9-58-27cd	Shell Oil Co.		U	Dr	482	7	P	Ss	- - do - -	CY	In	2,955			
10-55- 6da	Enebak-Haman Ranch		L	Dr	1,180			Ss	- - do - -		D	2,498	21.40	10- 4-62	
10-55-25dc	Bill Almy		L	Dr	1,150	4	P	Ss	- - do - -	CY	S	2,609	53.95	10- 4-62	
10-58-18-cd	Shell Oil Co.		U	Dr	395	7	P	Ss	- - do - -	S	In	2,772			
10-58-18dc	Unknown		U	Dr	166	4	P	Ss	- - do - -	CY	S	2,782	142.39	10- 2-63	
10-58-30cc	W. Fuchs		L	Dr	208	4	P		Khc	CY	S	2,960	49	10- 5-62	
10-58-32dbl	Shell Oil Co.		U	Dr	463	5	P	Ss	Kfh, Khc	N	N	2,912	214.78	10- 2-63	
10-58-32db2	- - - - do - - - -	1961	U	Dr	497	16-7	P	Ss	- - do - -	S	In	2,936			
11-54-28cc	A. Mathiason	1947	U	Dr	1,060	4-2	P	Ss	- - do - -	S	D	2,489	39.99	7-18-63	
11-54-29ca	City of Mildred		L	Dr	865	3	P	Ss	- - do - -	F	P	2,360			
11-54-30dd	Dick Kranzler		C	Dr	740	2	P	Ss	- - do - -	F	D, S	2,361			
11-55- 2ac	E. McNaney	1957	U	Dr	1,110	4-2	P	Ss	- - do - -	F	D	2,444		7-22-63	3 gpm flow
11-56- 2ca	Bureau of Land Management	1961	U	Dr	246	4	P		Tfu	CY	S	2,680	175.65	3-26-63	
11-56- 4bal	S. Irion		L	Dr	78	4	P		- - do - -	N	S	2,565	58.30	11- 7-62	
11-56- 4ba2	- - - - do - - - -	1962	L	Dr	1,220	5	P	Ss	Kfh, Khc	CY	D, S	2,565	91.4	10- 1-63	
11-56- 6dbl	O. Seteren	1941	L	Dr	937	2	P	Ss	- - do - -	S	D	2,439			
11-56- 6db2	- - - - do - - - -	1956	L	Dr	350	4	P		Tfu	F	S	2,439		8-30-63	1 gpm flow
11-56-20aa	- - - - do - - - -	1963	U	Dr	1,180	3	P	Ss	Kfh, Khc	F	S	2,490	+23.80	8- 6-63	9 gpm flow
11-56-26bb	R. Steffes	1945	L	Dr	882		P	Ss	- - do - -	F	D, S	2,510		8-29-63	1 gpm flow
11-57- 6cc	Shell Oil Co.	1962	U	Dr	1,263	12	P	Ss	- - do - -	S	In	2,801	308	10-13-62	
11-57- 7ab	B. Brownfield		U	Dr	53	4	P		Khc	N	N	2,750	53.58	10- 1-63	
11-57-17abl	Union Texas Pet.		L	Dr	170	8	P	Ss	Kfh, Khc	N	N	2,633	82.57	10- 1-63	
11-57-17ab2	- - - - do - - - -		L	Dr	300	8	P	Ss	- - do - -	N	N	2,642	102.54	10-12-62	
11-57-17bc	- - - - do - - - -	1958	U	Dr	1,190		P	Ss	- - do - -	S	In	2,652			
11-57-21cbl	E. McNaney	1947	U	Dr	105	7	P		Khc	N	N	2,630	62.40	10- 1-63	
11-57-21cb2	Shell Oil Co.		U	Dr	710	7	P	Ss	Kfh, Khc	T	In	2,695			
11-57-21cb3	- - - - do - - - -	1954	U	Dr	1,230		P	Ss	- - do - -	N	In	2,619	96.27	10- 1-63	
11-57-27cd	G. Rugg		C	Dr	115		P	Ss	Kfh	CY	S	2,585	22.11	10- 1-63	
11-57-32bb	A. McNaney	1959	L	Dr	980	4	P	Ss	Kfh, Khc	S	D, I	2,594	52	10-31-63	
12-53-23cal	F. Sackman		L	Dr	1,200	4-2	P	Ss	- - do - -	S	D, S	2,559	155.69	7- 1-63	
12-53-23ca2	- - - - do - - - -		L	Dr	163	4	P		Tfu	CY		2,559	140.90	8-30-63	
12-55- 8cc	J. D. Strobel		U	Dr	960	2	P	Ss	Kfh, Khc	F	S	2,323	+71.67	7-12-63	16 gpm flow
12-55-13dc	D. H. Baggott		U	Dr	1,135	4	P	Ss	- - do - -	CY	S	2,434	17.94	12-13-62	
12-55-15bc	Leo Lund		U	Dr	980	2	P	Ss	- - do - -	F	S	2,349	+48.66	7-12-63	15 gpm flow
12-55-16db	- - - - do - - - -		C	Dr	920	2	P	Ss	- - do - -	F	S	2,304	+90.30	7- 7-63	16 gpm flow
12-55-18ca	Unknown		L	Dr	57	36	C		Tfu	CY		2,495	46.08	10-17-62	
12-55-20dc	D. Hoffer	1946	L	Dr	1,185	4	P	Ss	Kfh, Khc		D	2,477	66.59	10-10-62	
12-55-21dd	J. D. Strobel		L	Dr	813	2	P	Ss	- - do - -	F	D, S	2,351			
12-55-22bc	Leo Lund	1946	L	Dr	860	2	P	Ss	- - do - -	F	D, S	2,336			
12-55-24cd	E. Hoffer		L	Dr	1,020	2	P	Ss	- - do - -	F	D	2,413			20 gpm flow
12-55-25dd	- - - - do - - - -		U	Dr	126	4	P		Tfu	CY	S	2,406	114.95	10-17-62	
12-55-25cd	Dave Strobel		U	Dr	1,275	4	P	Ss	Kfh, Khc	F	S	2,442		7-19-63	1 gpm flow
12-55-26bc	- - - - do - - - -	1913	L	Dr	1,100	2	P	Ss	- - do - -	F	D, S	2,369			
12-55-28bd	Alvin Stickel		L	Dr	1,002	2	P	Ss	- - do - -	F	D, S	2,381		11- 7-62	10 gpm flow
12-55-35ac	E. McNaney		C	Dr	180	1¼	P		Tfu	F	S	2,367		8- 8-63	6 gpm flow
12-55-36dd	Dave Strobel		U	Dr	1,140	2	P	Ss	Kfh, Khc	F	S	2,433	+18.57	8- 8-63	7 gpm flow
12-56- 2cc	B. Brownfield		U	Dr	70	6	P	Ss	Kfh	N	N	2,561	12.71	10- 1-63	
12-56-10ac	Shell Oil Co.		U	Dr	1,170	7	P	Ss	Kfh, Khc	CY	In	2,635			
12-56-19cd	D. H. Baggot		U	Dr	1,149	2	P	Ss	- - do - -	F	S	2,431	+9.67	8-11-63	4 gpm flow
12-56-23dc	Shell Oil Co.	1952	U	Dr	1,185	4	P	Ss	- - do - -	N	In	2,703	365.80	10- 1-63	
12-56-23cc	- - - - do - - - -	1962	U	Dr	1,449	10	P	Ss	- - do - -	S	In	2,672	187.4	10-13-62	
12-56-24ca	B. Brownfield		U	Dr	145	4	P	Ss	Kfh	CY	N	2,654	112.67	10- 1-63	
12-56-25cb	Shell Oil Co.	1962	U	Dr	1,480	10	P	Ss	Kfh, Khc	N	In	2,758	291.98	10- 1-63	
12-56-26db	S. Irion		U	Dr	110	4	P		Tfu	CY	S	2,587	29.92	10- 1-63	
12-56-26ab	Shell Oil Co.		U	Dr	1,185	6	P	Ss	Kfh, Khc	N	In	2,690	247.24	10- 1-63	
12-56-34da	- - - - do - - - -	1962	U	Dr	1,467	4	P	Ss	- - do - -	N	In	2,710	253.29	10- 1-63	
13-54-10bb	I. Schock		L	Dr	1,020	2	P	Ss	- - do - -	F	D, S	2,223	+42.80	7-11-63	38 gpm flow
13-54-18ac	Marsh School District		U	Dr	800 (?)	2	P	Ss	- - do - -	F	N	2,194	+65.05	8-10-63	1 gpm flow
13-54-22ca	F. J. Haidle	1961	C	Dr	915	2	P	Ss	- - do - -	F	S	2,196	+155.90	8-10-63	37 gpm flow
13-55-18dc	J. Kaul		L	Dr	135 (?)		P		Tfu	CY	S	2,269	43.3	8-28-63	
13-55-25da	Unknown		U	Dr	100	4	P	Ss	Kfh	CY	S	2,441	31.88	7-26-63	
13-55-30ac	J. Opp	1959	U	Dr	1,180	2	P	Ss	Kfh, Khc	F	D, S	2,346	+14.55	7-11-63	10 gpm flow
14-54-25bb	Krug Ranch	1960	C	Dr	816	2	P	Ss	- - do - -	F	S	2,118	+182	8-11-63	25 gpm flow
14-54-34cb	- - - - do - - - -		C	Dr	816	2	P	Ss	- - do - -	F	D, S	2,128			
							Eastern Flank								
7-61- 6ac	L. Jensen	1963	U	Dr	336	3	P	Ss	Kfh, Khc		D, S	3,164	190	1963	
8-60- 2db	T. Bruha	1956	U	Dr	402	4	P	Ss	- - do - -	S	D, S	3,150	215	1956	
8-61- 2cd	- - - - do - - - -	1961	C	Dr	323	4	P	Ss	- - do - -	CY	S	2,875	8	1963	
9-59-33dc	School Dist.		U	Dr	100	4	P	Ss	- - do - -	CY	N	3,064	71.00	4-27-64	
9-60-23bb	W. Malcom	1956	L	Dr	867	3-2	P	Ss	- - do - -	CY	D, S	3,357	380	1956	
9-60-30bc	W. Schweigert		U	Dr	540	4-2	P	Ss	- - do - -	S	D, S	3,154	190	1956	
10-58-25aa	Unknown		L	Dr	80	3	P	Ss	- - do - -	CY	N	2,854	57.23	4-28-64	
10-59-22dd	Rush Hall		U	Dr	225	6	P	Ss	- - do - -	CY	S	3,010	161.30	4-28-64	
10-61-31ba	R. Rustad	1962	L	Dr	140	5-2	P	Ss	Khc	F	S	3,059			1 gpm flow
11-59-29ac	S. Nelson	1947	U	Dr	536	4	P	Ss	Kfh, Khc		D	3,193	436	1947	
12-58-16ab	W. H. Peterman	1960	U	Dr	350	4	P	Ss	- - do - -	CY	S	2,837	270	1960	
12-59-32aa	A. Hanson	1959	U	Dr	650	6	P	Ss	- - do - -	CY	D, S	3,129	500	1959	
13-59-35ad	Unknown		L	Dr	29	4	P	Ss	Tfu	CY	S	2,797	14.72	5- 1-64	
14-59-34dd	Rex Knight		U	Dr	160	4	P	Ss	- - do - -	CY	N	2,841	87.49	4-29-64	



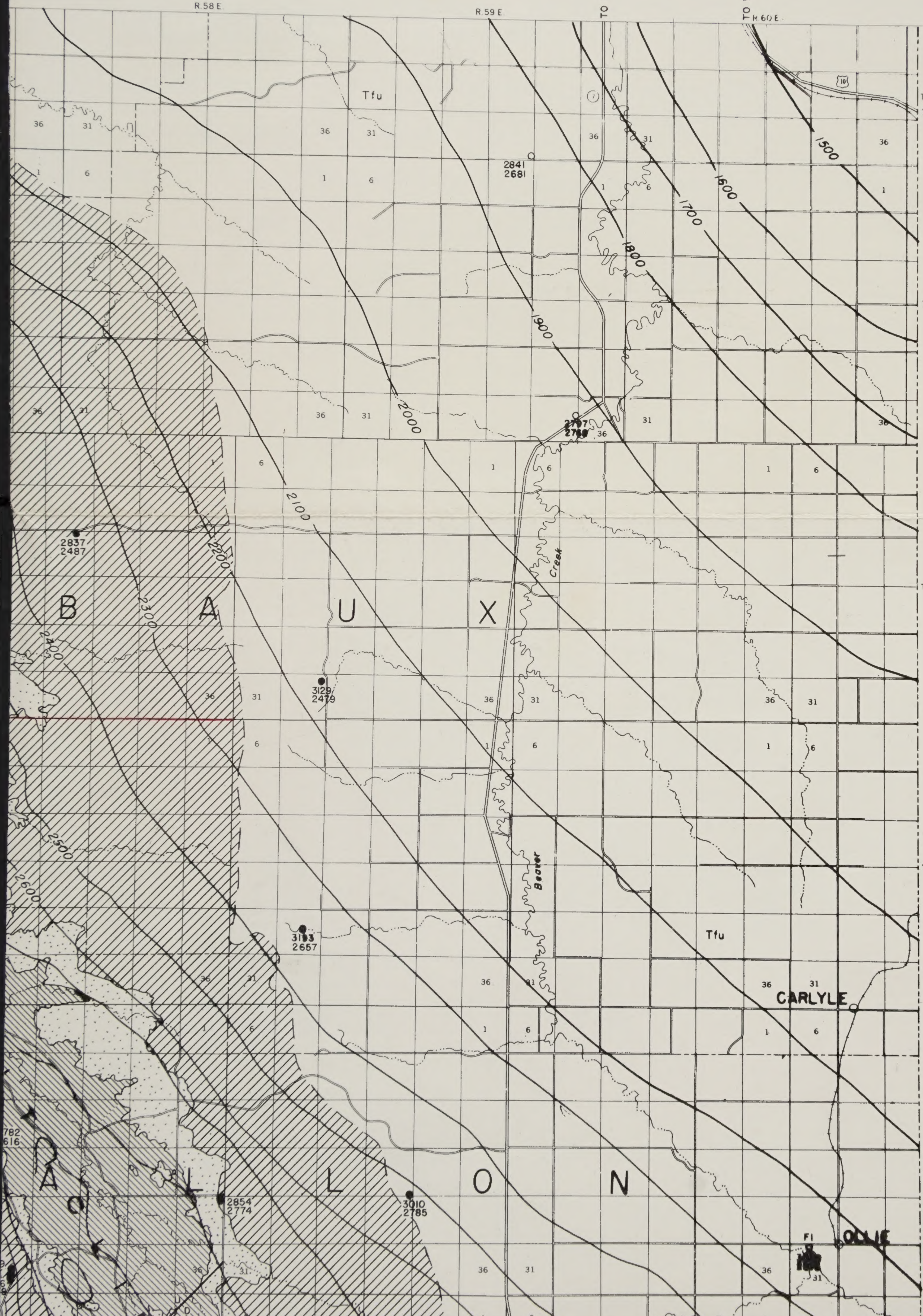
GEOLOGY, STRUCTURAL CONTOURS, AND WATER WELLS ALONG THE CEDAR CREEK ANTICLINE IN CUSTER, DAWSON, FALLON, PRAIRIE, AND WIBAUX COUNTIES, MONTANA

150 Kfh
600 Khc

MONTANA BUREAU OF MINES AND GEOLOGY



MEMOIR 40 PLATE I



EXPLANATION

TERTIARY

Paleocene

Tfu

Fort Union Formation

Shale, sandstone, siltstone, and lignite beds. Consists of Tongue River and Ludlow Members

CRETACEOUS

Upper Cretaceous

Khc

Hell Creek Formation

Light-green to brown sandstone and shale, mudstone, siltstone, concretions

Montana Group

Kfh

Fox Hills Sandstone

Light-brown to yellow-brown sandstone and siltstone. Locally light-gray Colgate Member at top

Kp

Pierre Shale

Predominantly dark-gray shale with sandstone, gypsum, and concretions

1900 — Structure contour drawn on base of Fox Hills Sandstone. Contour interval 100 feet, except along western flank of Cedar Creek anticline; datum is mean sea level.

● Water well completed in aquifer in Fox Hills Sandstone and basal part of Hell Creek Formation.

○ Water well completed in upper part of Hell Creek or in Fort Union Formation.

F10 ○ / F4 ● Flowing water well with flow in gallons per minute

○ 2975 2725 / ● 2490 1310 Water well with altitudes of land surface and bottom of well, in feet

Geologic contact. Dashed where approximately located

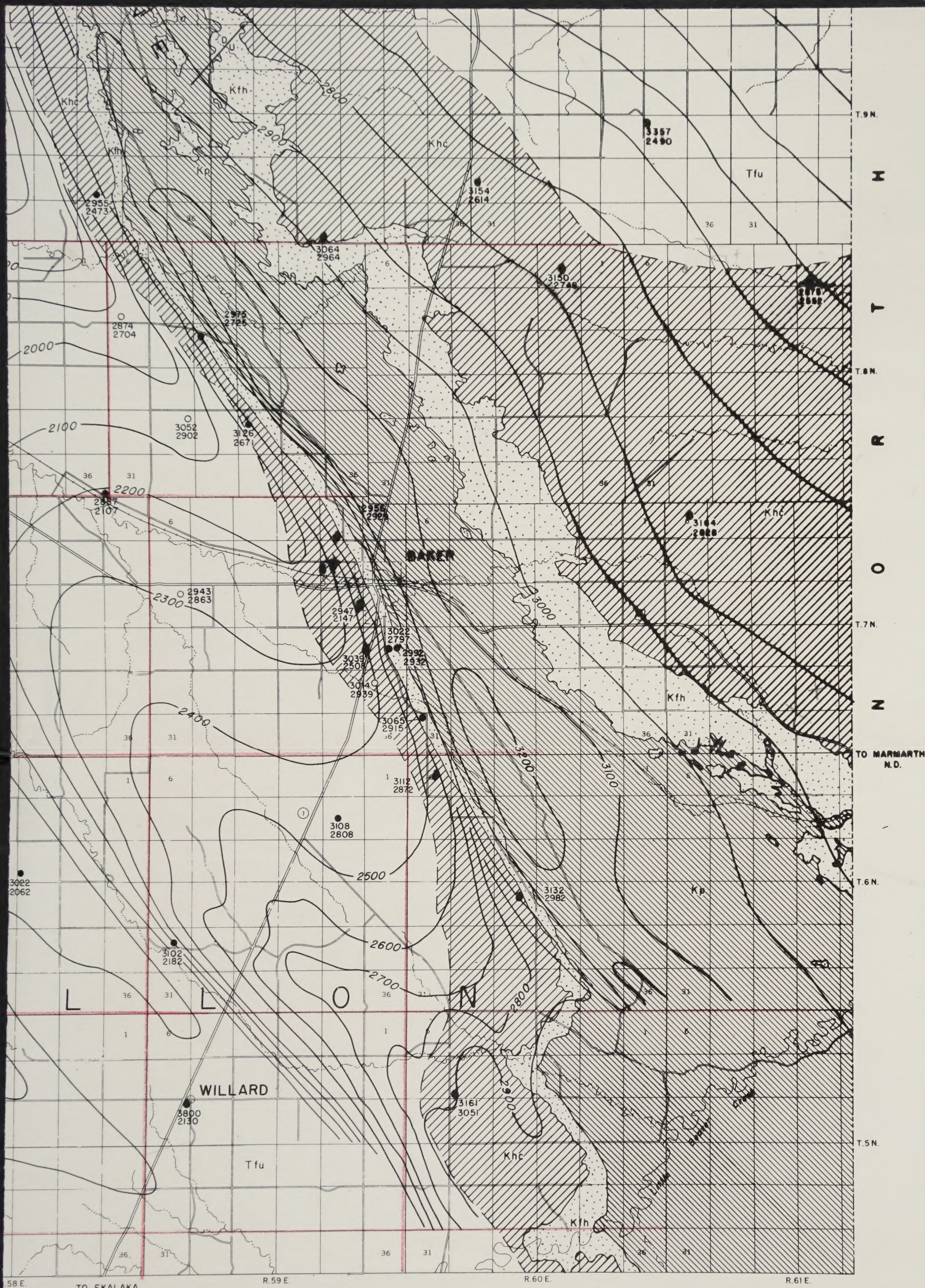
U D Fault; U upthrown, D downthrown side

Geology by Erdmann and Larsen (1934), Dobbin and Larsen (1934) and Brown (1949)

Structural contours furnished by Shell Oil

GEOLOGY, STRUCTURAL CONTOURS, AND WATER WELLS

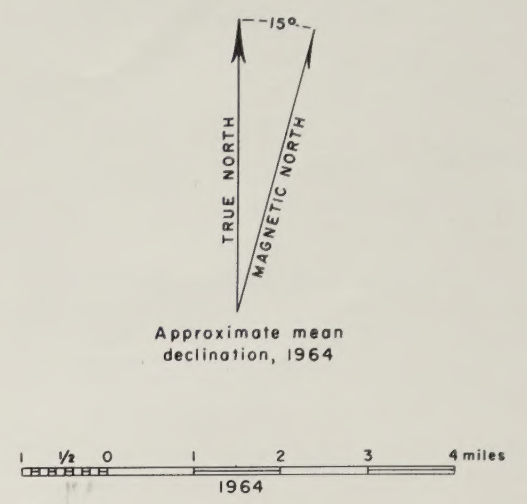
IN CUSTER, DAWSON, FALLON, PRAIRIE, AND W



Co. (1962).

Hydrology by O. James Taylor (1964)

Base compiled from maps by Montana State Highway Department (1961).



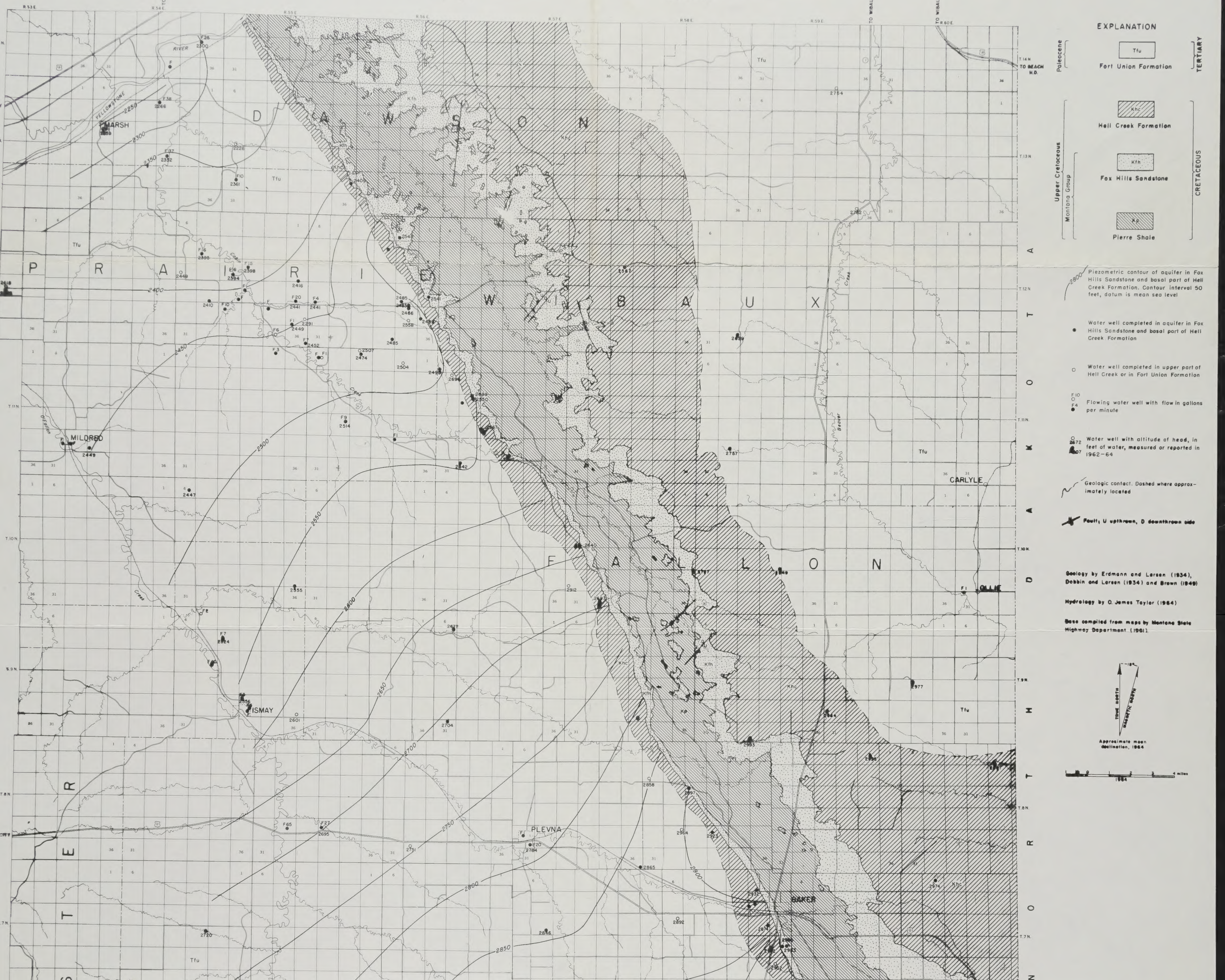
150-250

S ALONG THE CEDAR CREEK ANTICLINE

VIBAUX COUNTIES, MONTANA

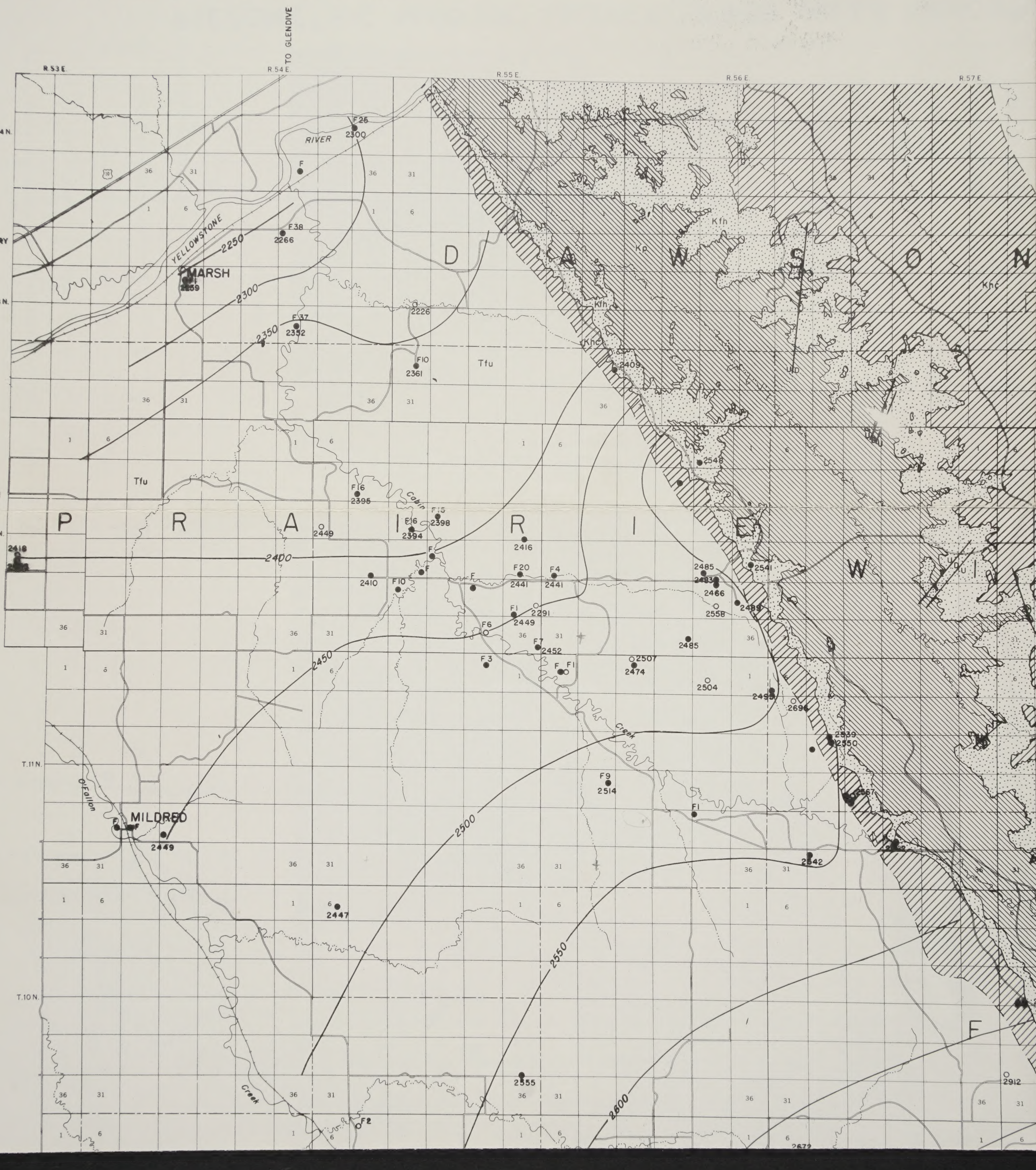
MONTANA BUREAU OF MINES AND GEOLOGY

MEMOIR 40 PLATE 2

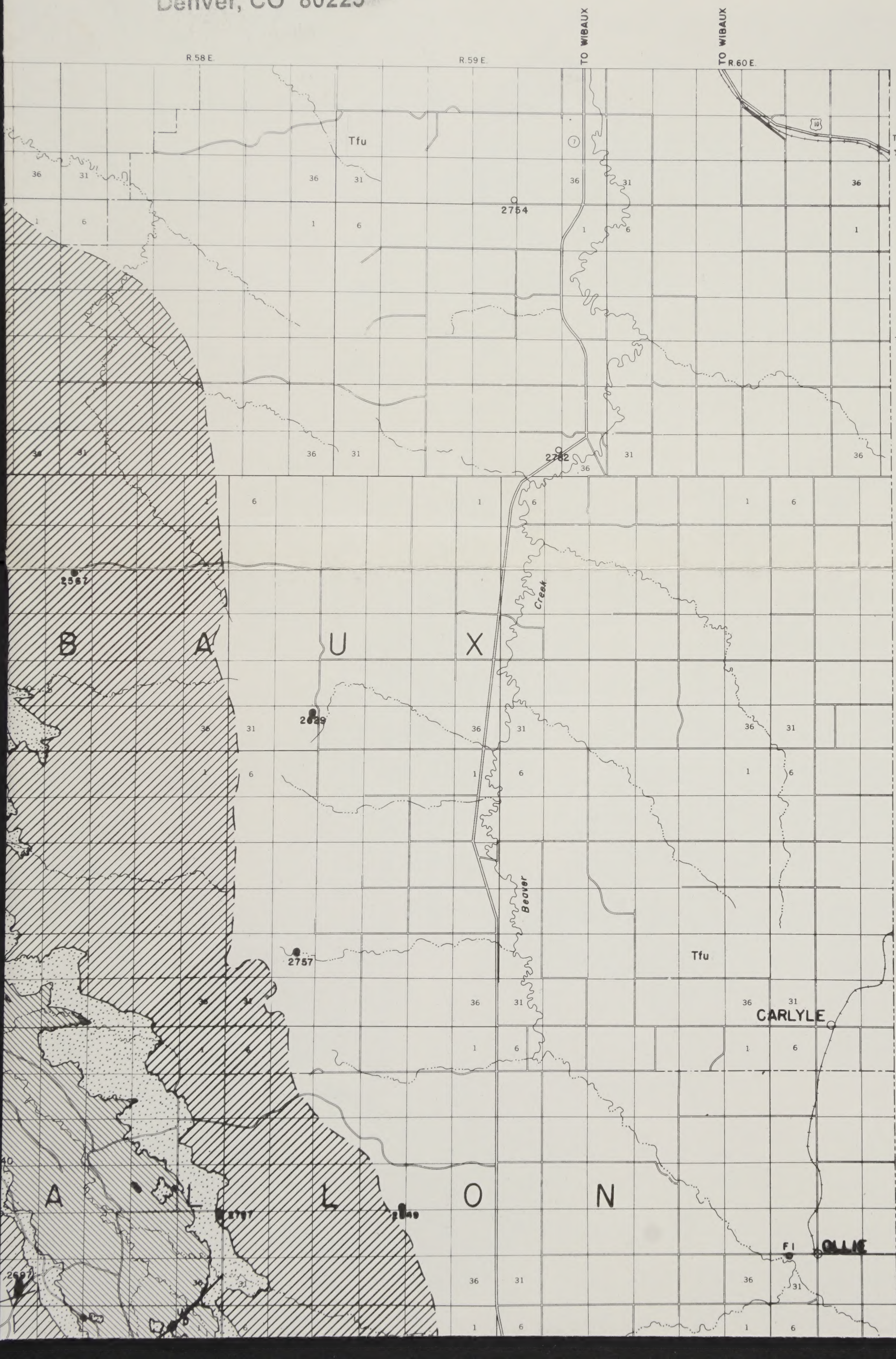


PIEZOMETRIC MAP OF AQUIFER IN FOX HILLS SANDSTONE AND BASAL PART OF HELL CREEK FORMATION ON WESTERN FLANK OF THE CEDAR CREEK ANTICLINE

MONTANA BUREAU OF MINES AND GEOLOGY



MEMOIR 40 PLATE 2



EXPLANATION

Paleocene — Tfu — Fort Union Formation — TERTIARY

Upper Cretaceous — Khc — Hell Creek Formation — CRETACEOUS

Montana Group — Kfh — Fox Hills Sandstone

Kp — Pierre Shale

2800 — Piezometric contour of aquifer in Fox Hills Sandstone and basal part of Hell Creek Formation. Contour interval 50 feet, datum is mean sea level

Water well completed in aquifer in Fox Hills Sandstone and basal part of Hell Creek Formation

Water well completed in upper part of Hell Creek or in Fort Union Formation

F10, F4 — Flowing water well with flow in gallons per minute

2672, 2607 — Water well with altitude of head, in feet of water, measured or reported in 1962–64

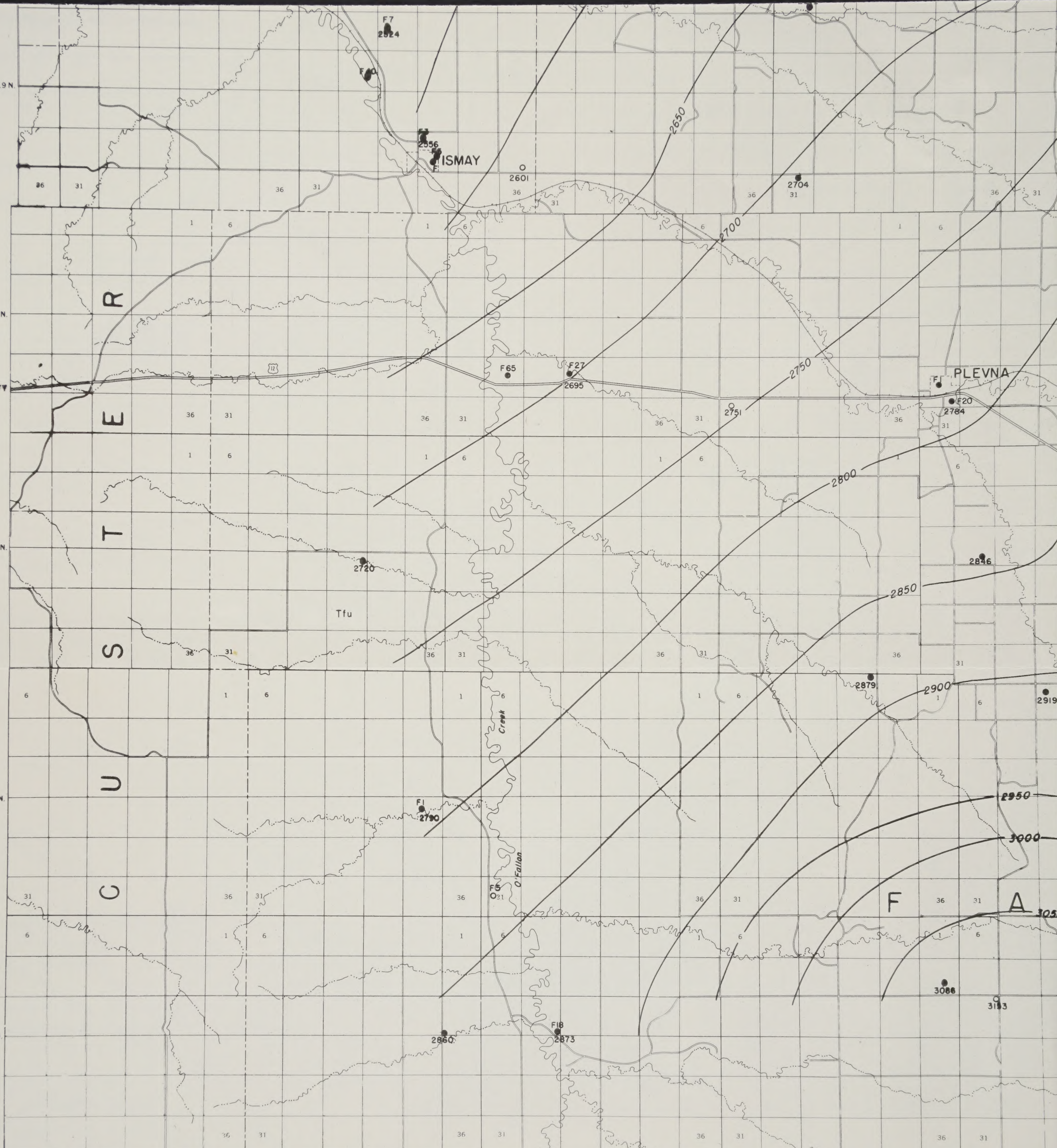
Geologic contact. Dashed where approximately located

Fault; U upthrown, D downthrown side

Geology by Erdmann and Larsen (1934), Dobbin and Larsen (1934) and Brown (1949)

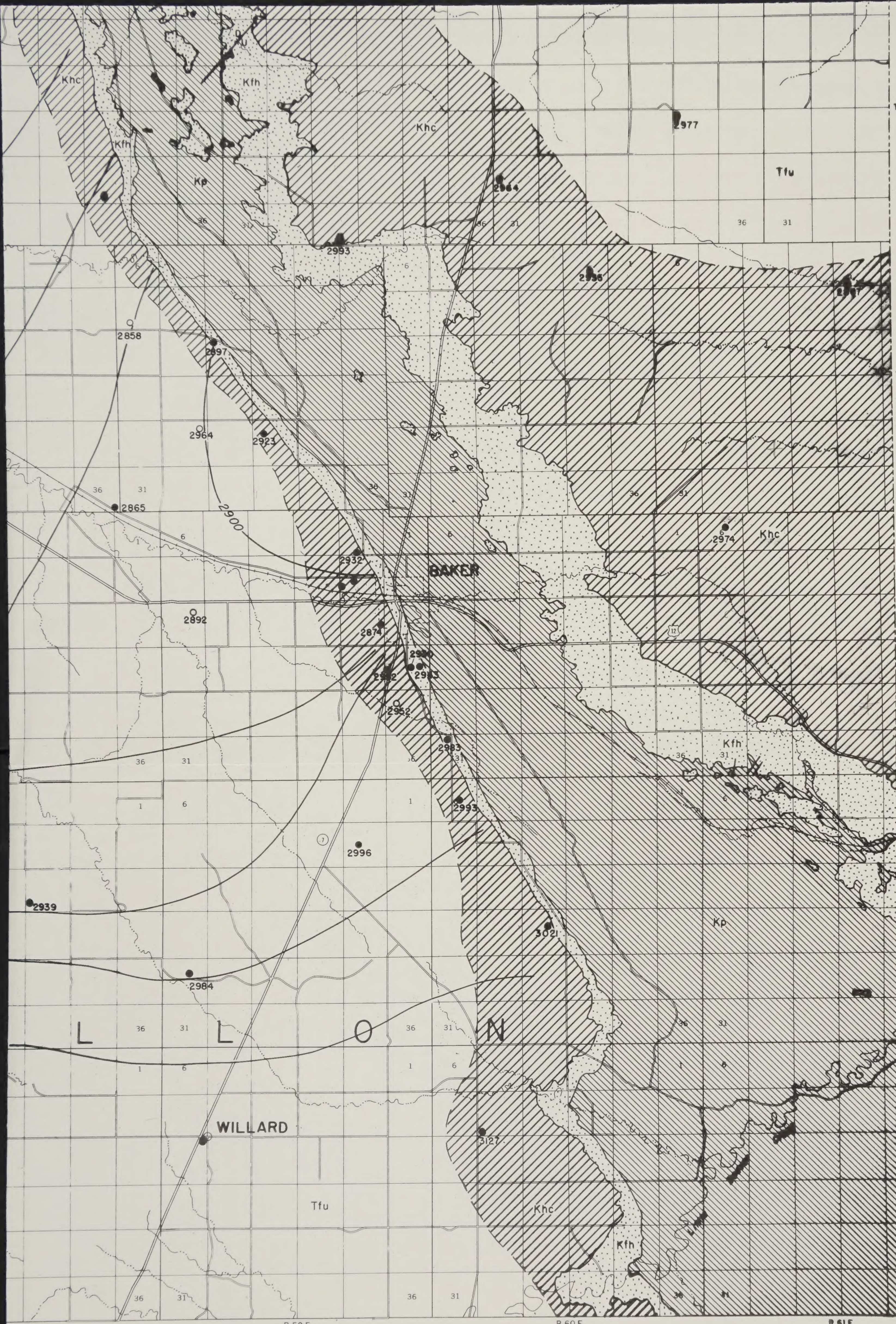
Hydrology by O. James Taylor (1964)

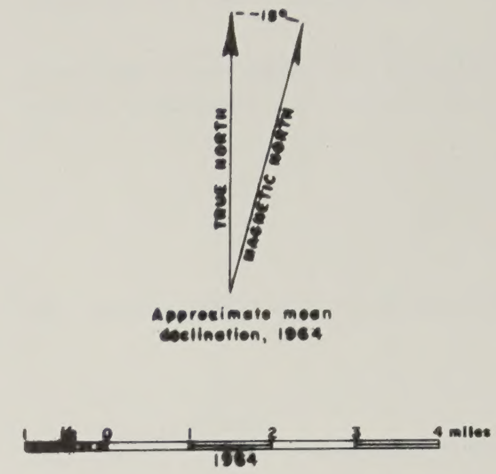
Base compiled from maps by Montana State Highway Department (1961)



PIEZOMETRIC MAP OF AQUIFER IN FOX HILLS SANDSTO

FORMATION ON WESTERN FLANK OF THE

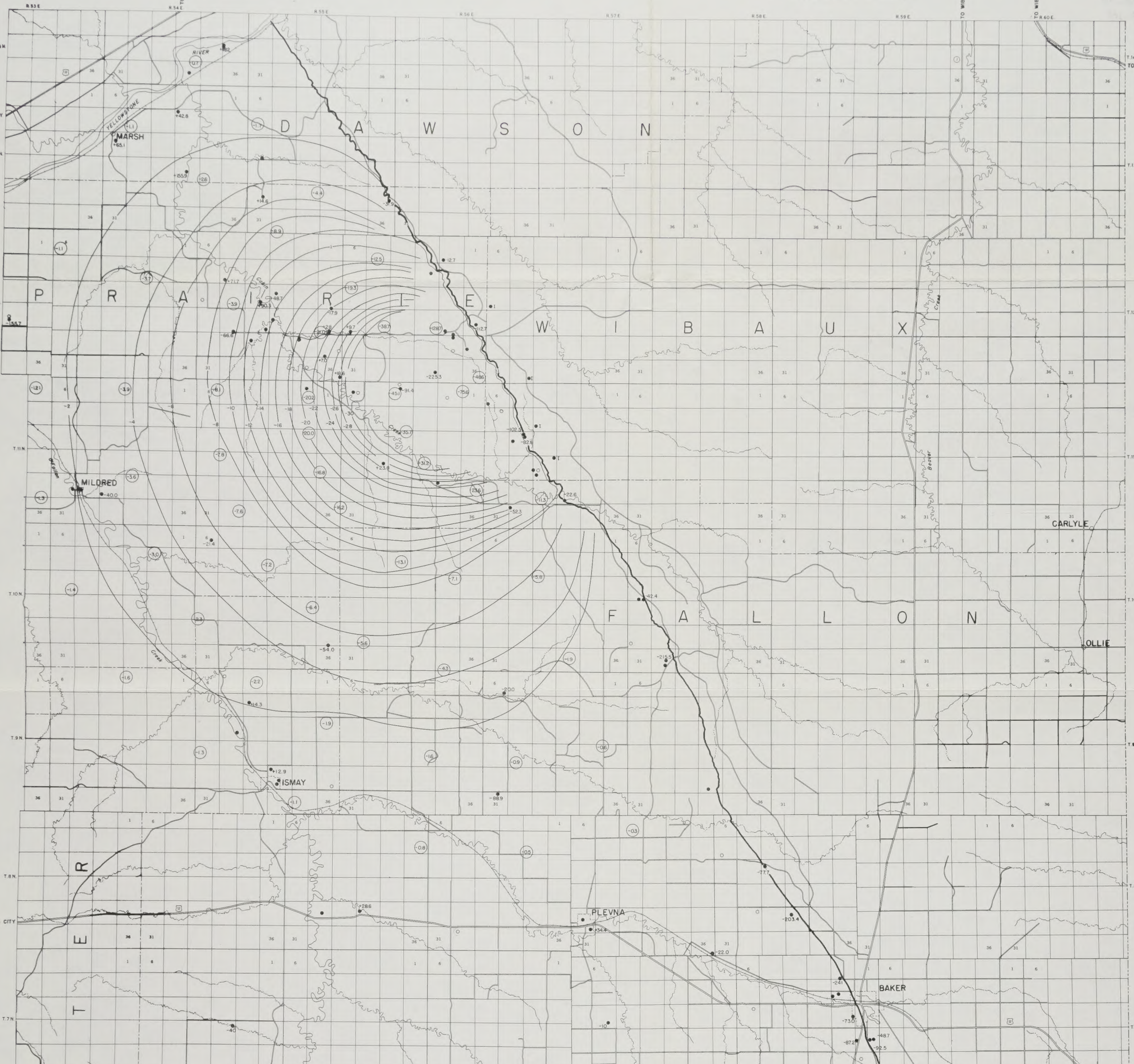




ONE AND BASAL PART OF HELL CREEK
CEDAR CREEK ANTICLINE

MONTANA BUREAU OF MINES AND GEOLOGY

MEMOIR 40 PLATE 3



EXPLANATION

Water well completed in aquifer in Fox Hills Sandstone and basal part of Hell Creek Formation

Water well completed in upper part of Hell Creek or in Fort Union Formation

Image well

+40.9 Water well with head, in feet, above land surface in 1962–63 before major industrial withdrawals

-112.7 Water well with head, in feet, below land surface in 1962–63 before major industrial withdrawals

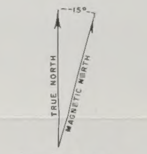
Centerline of outcrop of aquifer in Fox Hills Sandstone and basal part of Hell Creek Formation along which no drawdown is expected

5.7 Control point showing decline, in feet, in piezometric surface by the end of 1968 due to industrial withdrawals

-4 Depression contour showing decline, in feet, in piezometric surface by the end of 1968 due to industrial withdrawals

Hydrology by O. James Taylor (1964)

Base compiled from maps by Montana State Highway Department (1961).

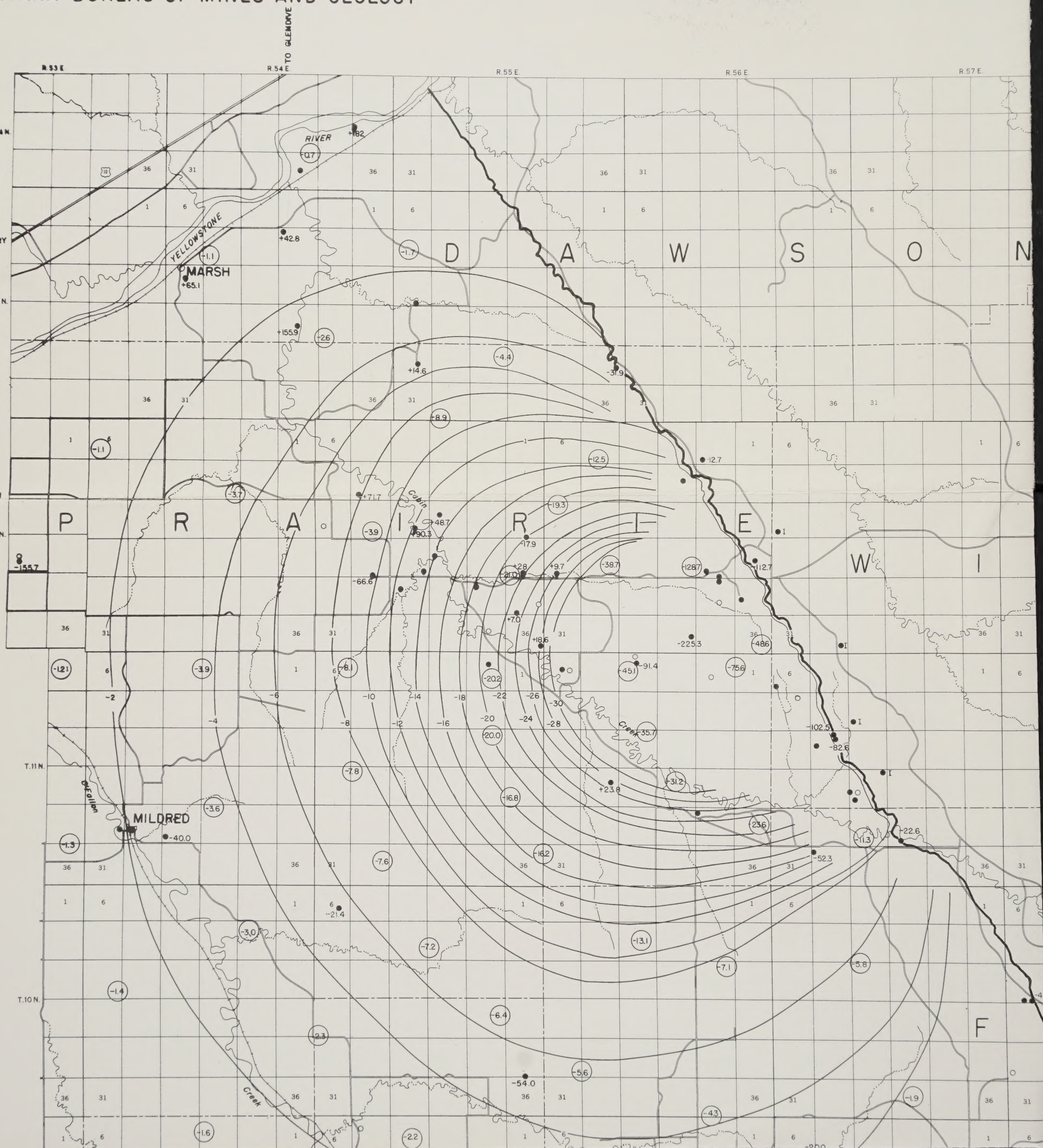


Approximate mean declination, 1964

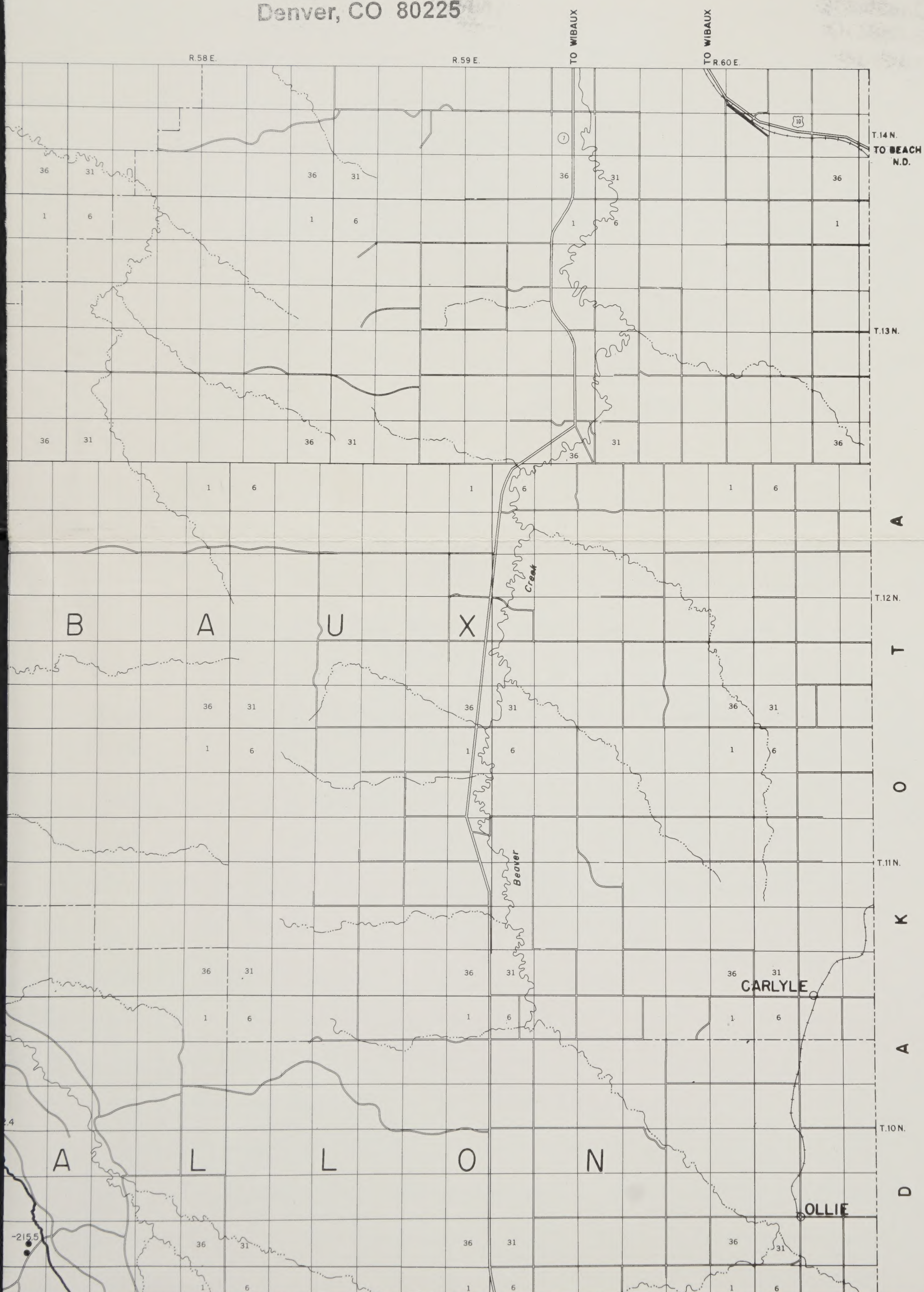
1 ½ 0 1 2 3 4 miles
1964

DEPRESSION CONTOUR MAP FOR THE PIEZOMETRIC SURFACE OF AQUIFER IN FOX HILLS SANDSTONE AND BASAL PART OF HELL CREEK FORMATION AT THE END OF ~~1963~~ 1968

MONTANA BUREAU OF MINES AND GEOLOGY



MEMOIR 40 PLATE 3



EXPLANATION

Water well completed in aquifer in Fox Hills Sandstone and basal part of Hell Creek Formation

Water well completed in upper part of Hell Creek or in Fort Union Formation

I Image well

+40.9 Water well with head, in feet, above land surface in 1962–63 before major industrial withdrawals

-112.7 Water well with head, in feet, below land surface in 1962–63 before major industrial withdrawals

Centerline of outcrop of aquifer in Fox Hills Sandstone and basal part of Hell Creek Formation along which no drawdown is expected

5.7 Control point showing decline, in feet, in piezometric surface by the end of 1968 due to industrial withdrawals

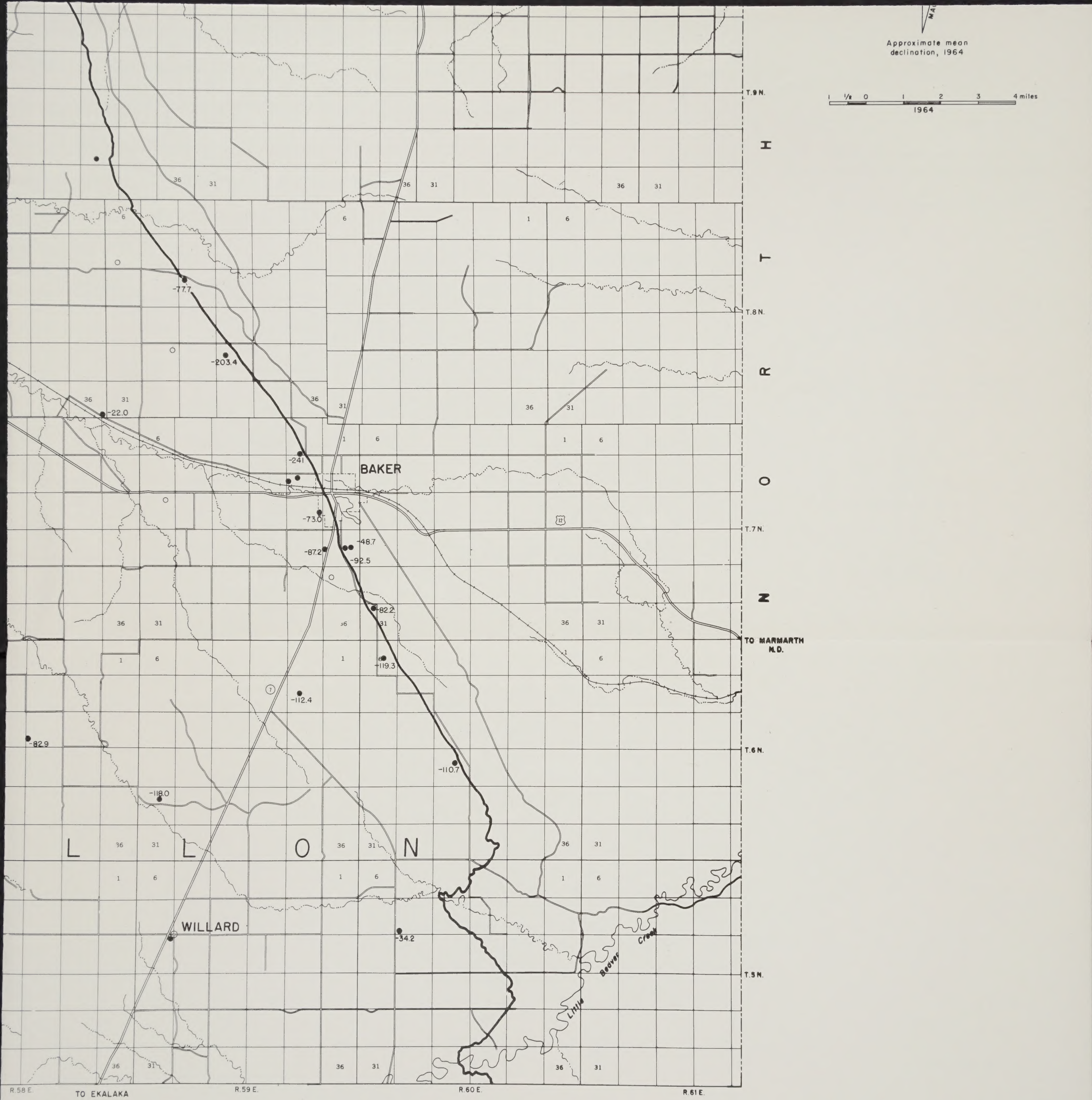
-4 Depression contour showing decline, in feet, in piezometric surface by the end of 1968 due to industrial withdrawals

Hydrology by O. James Taylor (1964)

Base compiled from maps by Montana State Highway Department (1961).

15°
TRUE NORTH
MAGNETIC NORTH

DEPRESSION CONTOUR MAP FOR THE PIEZOMETRIC
SANDSTONE AND BASAL PART OF HELL CREEK



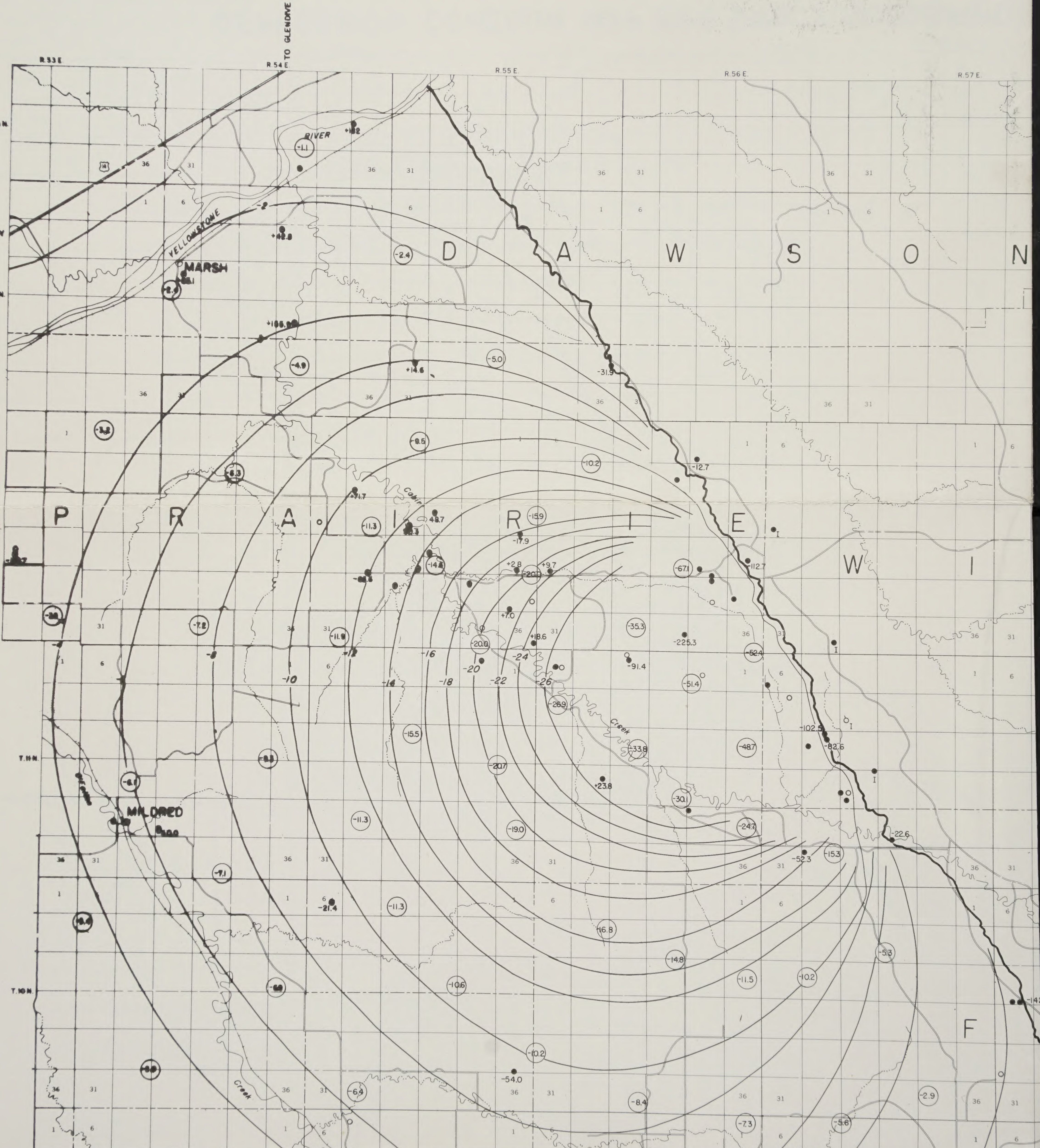
SURFACE OF AQUIFER IN FOX HILLS
FORMATION AT THE END OF ~~1963~~ 1968

MONTANA BUREAU OF MINES AND GEOLOGY

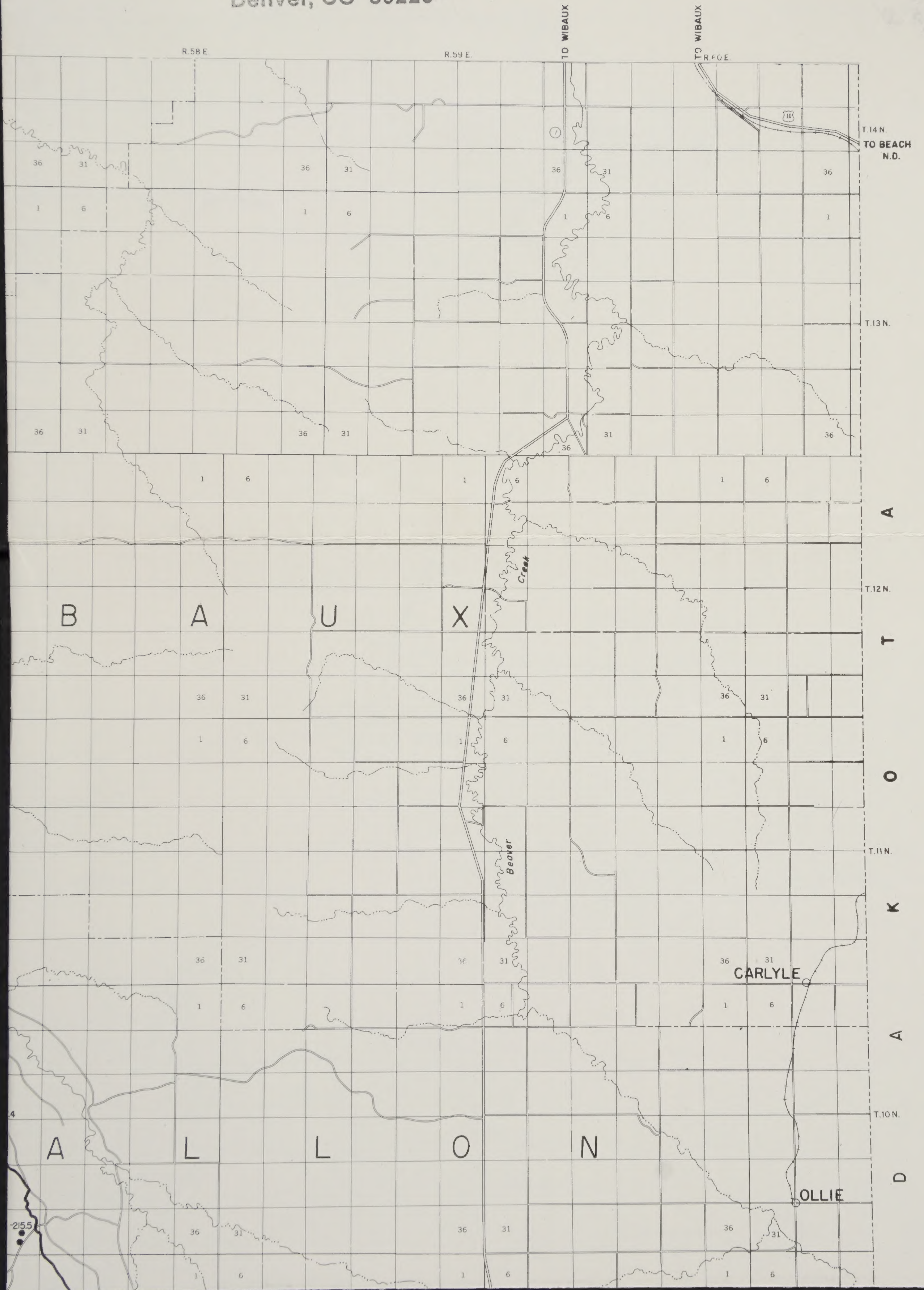
MEMOIR 40 PLATE 4

DEPRESSION CONTOUR MAP FOR THE PIEZOMETRIC SURFACE OF AQUIFER IN FOX HILLS SANDSTONE AND BASAL PART OF HELL CREEK FORMATION AT THE END OF 1973

MONTANA BUREAU OF MINES AND GEOLOGY



MEMOIR 40 PLATE 4



EXPLANATION

Water well completed in aquifer in Fox Hills Sandstone and basal part of Hell Creek Formation

Water well completed in upper part of Hell Creek or in Fort Union Formation

Image well

+40.9 Water well with head, in feet, above land surface in 1962-63 before major industrial withdrawals

-112.7 Water well with head, in feet, below land surface in 1962-63 before major industrial withdrawals

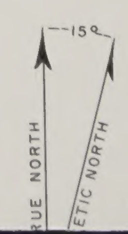
Centerline of outcrop of aquifer in Fox Hills Sandstone and basal part of Hell Creek Formation along which no drawdown is expected

(-5.7) Control point showing decline, in feet, in piezometric surface by the end of 1973 due to industrial withdrawals

-4 Depression contour showing decline, in feet, in piezometric surface by the end of 1973 due to industrial withdrawals

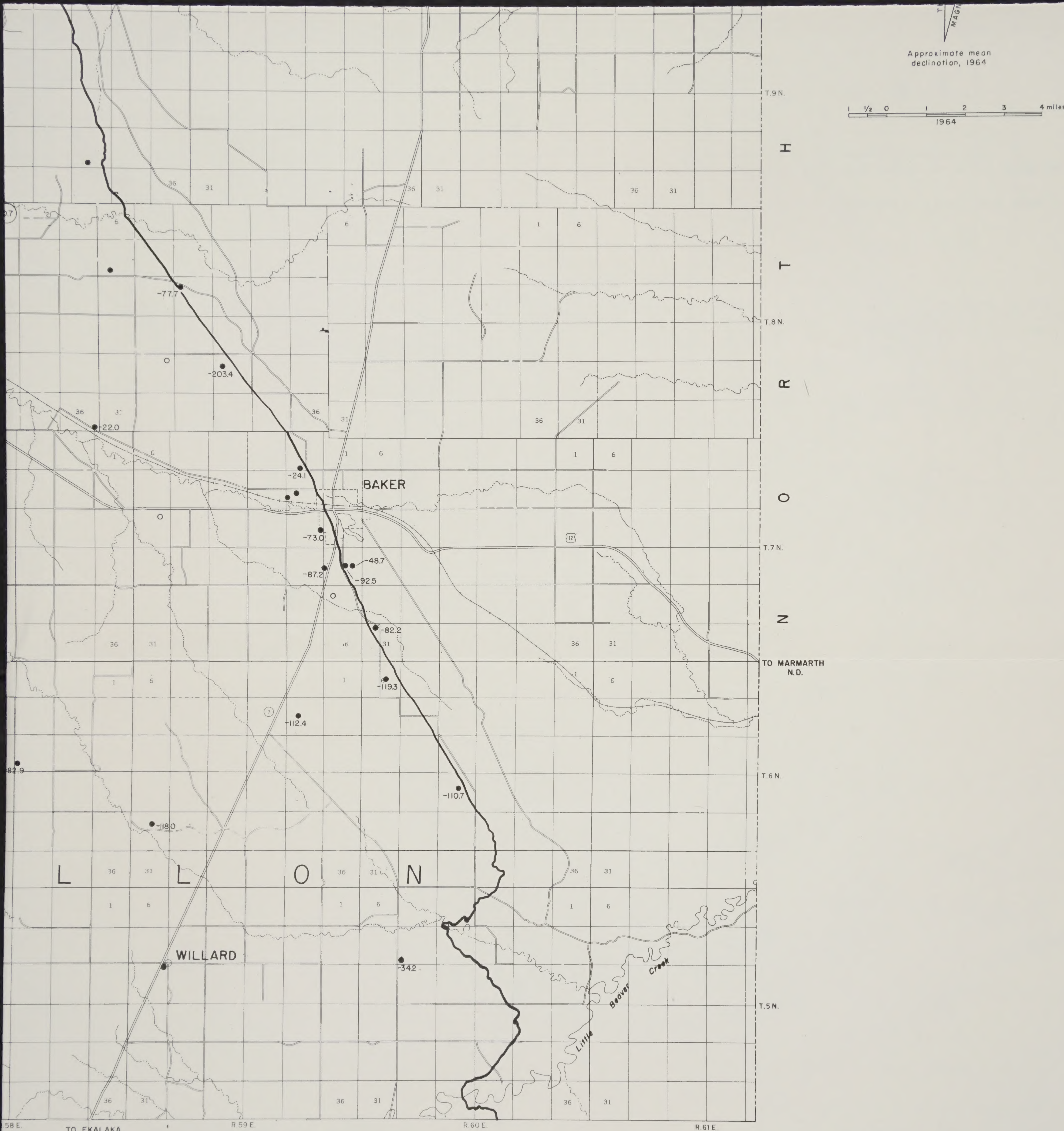
Hydrology by O. James Taylor (1964)

Base compiled from maps by Montana State Highway Department (1961).



DEPRESSION CONTOUR MAP FOR THE PIEZOMETRIC

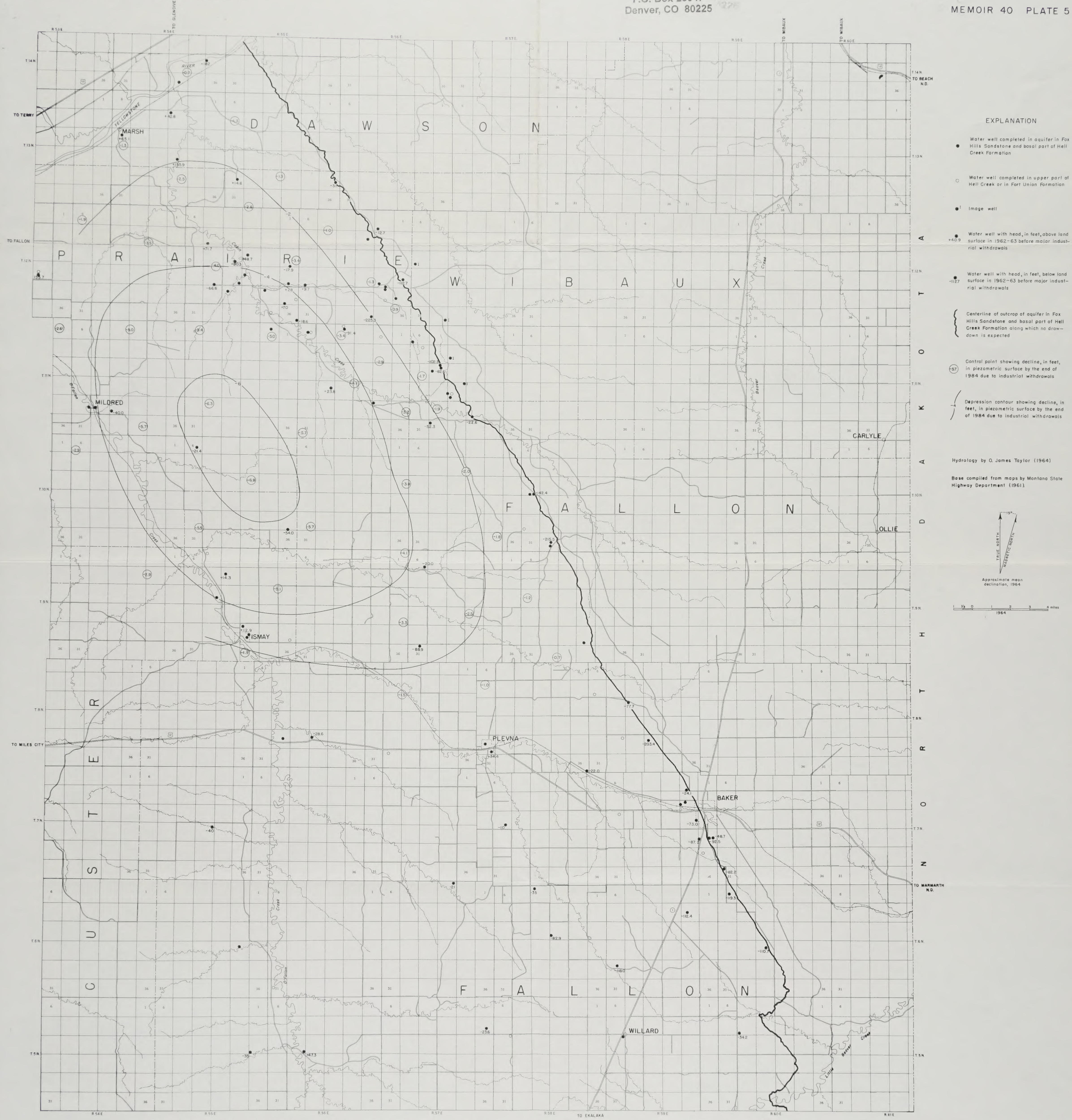
SANDSTONE AND BASAL PART OF HELL CREEK F



SURFACE OF AQUIFER IN FOX HILLS
ORMATION AT THE END OF 1973

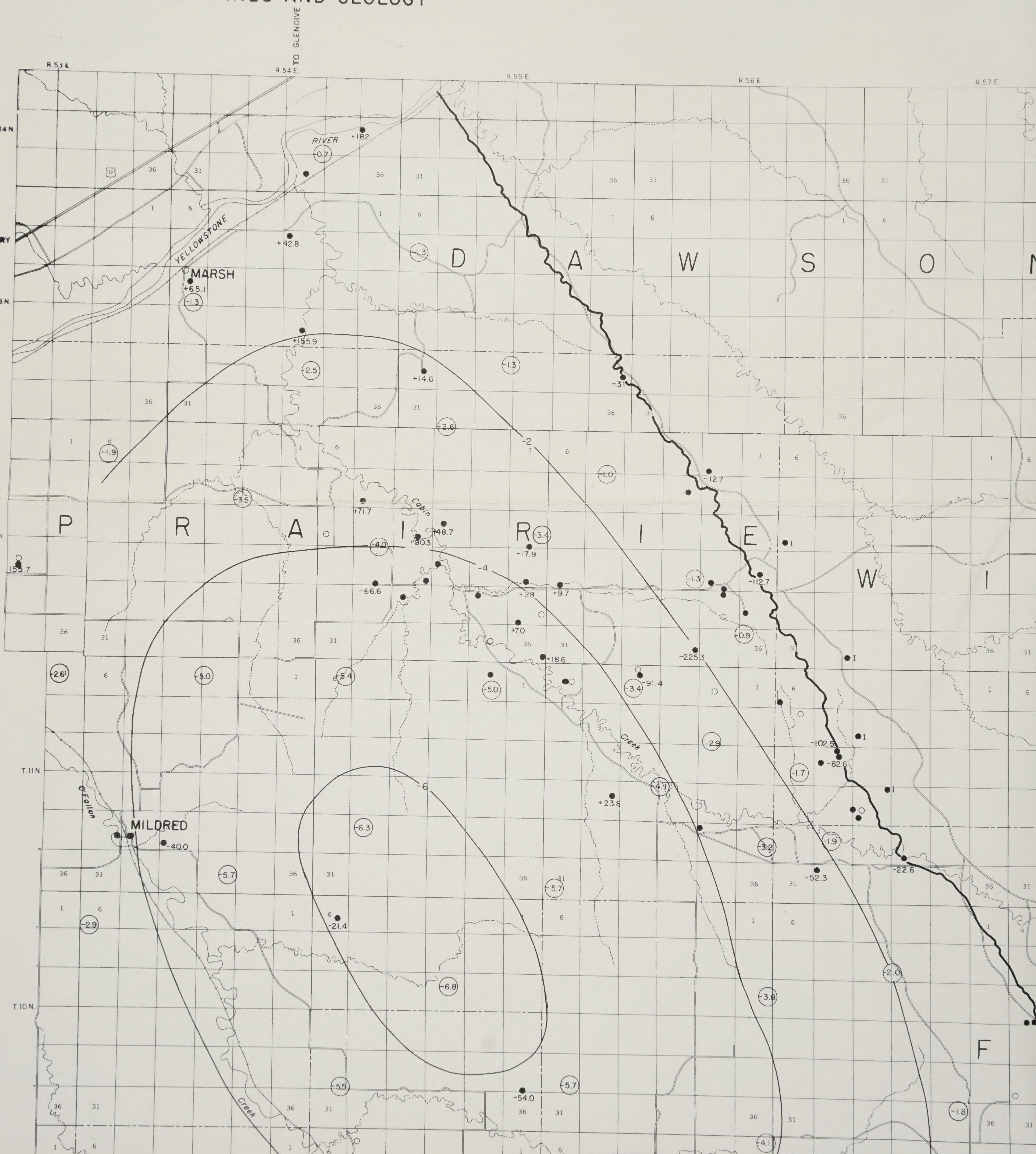
MONTANA BUREAU OF MINES AND GEOLOGY

MEMOIR 40 PLATE 5

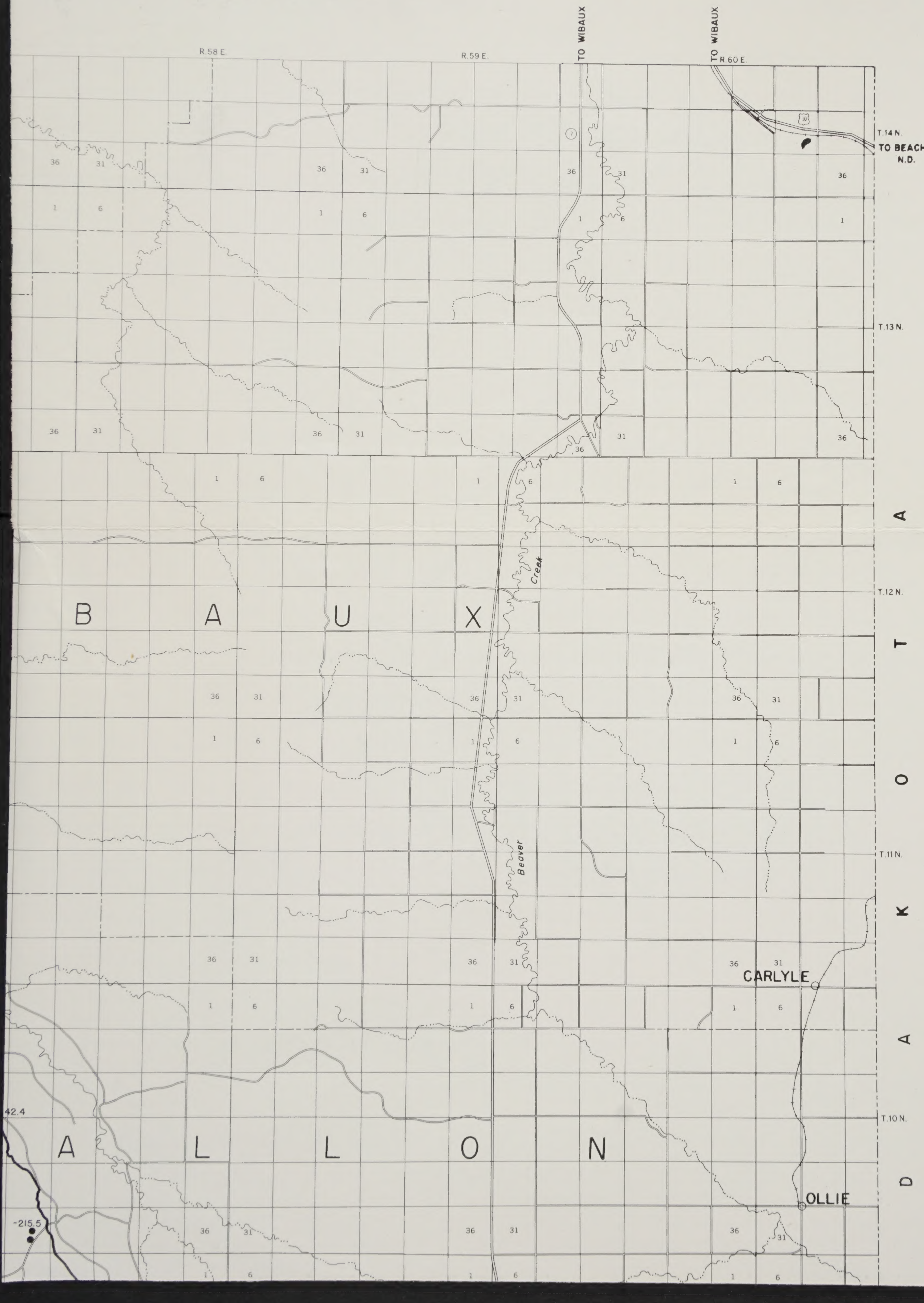


DEPRESSION CONTOUR MAP FOR THE PIEZOMETRIC SURFACE OF AQUIFER IN FOX HILLS SANDSTONE AND BASAL PART OF HELL CREEK FORMATION AT THE END OF 1984

MONTANA BUREAU OF MINES AND GEOLOGY



MEMOIR 40 PLATE 5



EXPLANATION

Water well completed in aquifer in Fox Hills Sandstone and basal part of Hell Creek Formation

Water well completed in upper part of Hell Creek or in Fort Union Formation

Image well

+40.9 Water well with head, in feet, above land surface in 1962-63 before major industrial withdrawals

-112.7 Water well with head, in feet, below land surface in 1962-63 before major industrial withdrawals

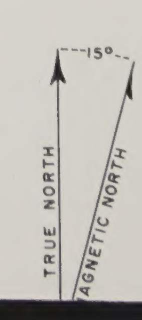
Centerline of outcrop of aquifer in Fox Hills Sandstone and basal part of Hell Creek Formation along which no drawdown is expected

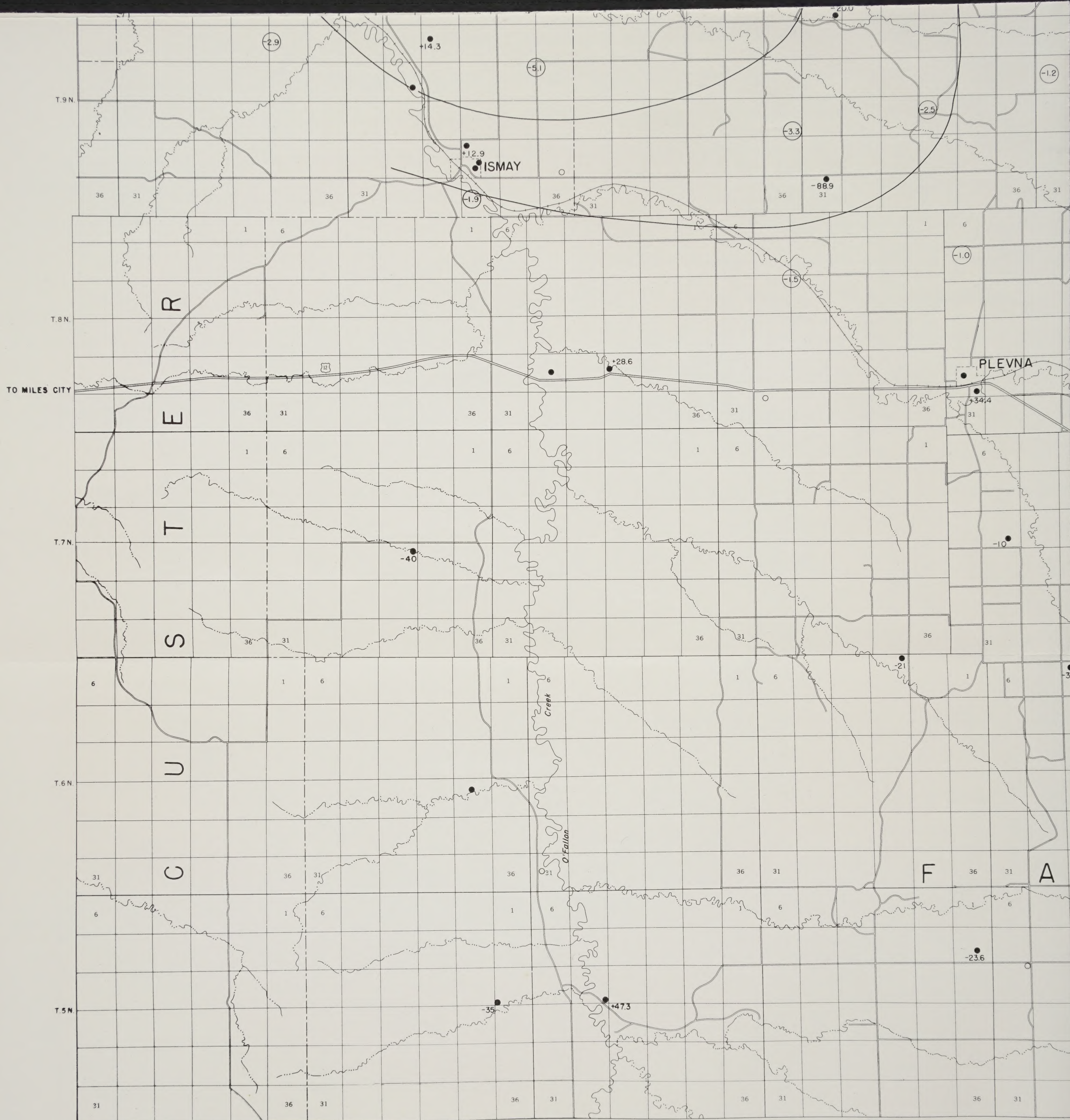
-57 Control point showing decline, in feet, in piezometric surface by the end of 1984 due to industrial withdrawals

-4 Depression contour showing decline, in feet, in piezometric surface by the end of 1984 due to industrial withdrawals

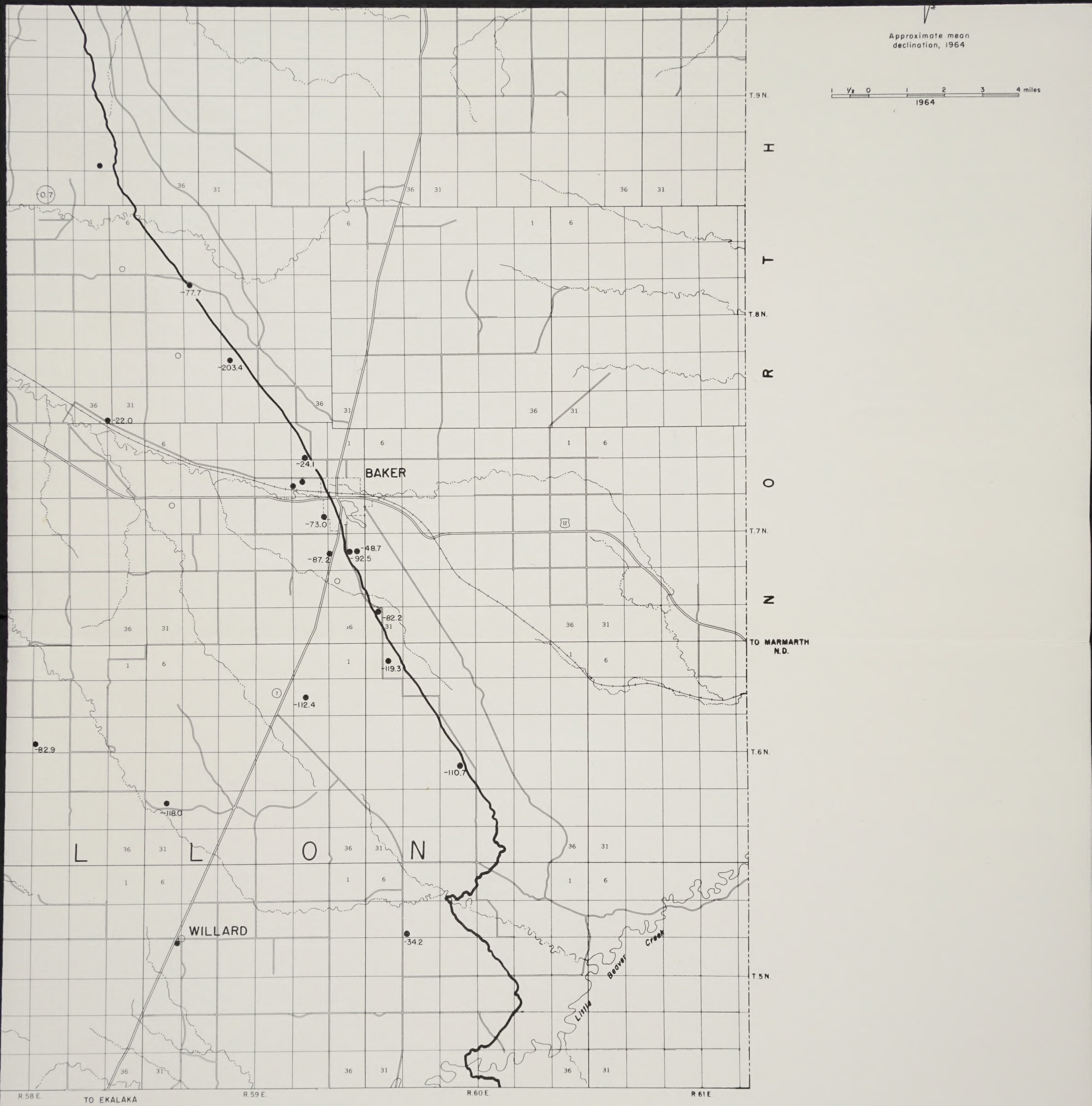
Hydrology by O. James Taylor (1964)

Base compiled from maps by Montana State Highway Department (1961).





DEPRESSION CONTOUR MAP FOR THE PIEZOMETRIC
SANDSTONE AND BASAL PART OF HELL CREEK



SURFACE OF AQUIFER IN FOX HILLS FORMATION AT THE END OF 1984

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FOR FURTHER INFORMATION, ADDRESS THE DIRECTOR, MONTANA BUREAU OF MINES AND GEOLOGY, MONTANA SCHOOL OF MINES, BUTTE.

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